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DISCUSSION ON LUBRICATION

HELD AT

THE IMPERIAL COLLEGE OF SCIENCE AND TECHNOLOGY

ON NOVEMBER 28TH, 1919.

PAPERS IN TYPE BEFORE THE MEETING.

Oiliness and Lubrication. *By* R. MOUNTFORD DEELEY.

COMMUNICATED BY THE LUBRICANTS AND LUBRICATION COMMITTEE.

WHEN metallic, or other surfaces, in contact are caused to slide over each other, considerable frictional resistance to motion results and the surfaces abrade each other. In machinery there are numerous rubbing surfaces, and the materials in contact must slide over each other with as little frictional resistance and as little wear as possible. Engineers have found by experience that the resistance to motion of such bearing surfaces, and the amount of abrasion or wear they suffer may be greatly reduced by interposing between them certain liquids or greases, known as lubricants.

Not all liquids will act as lubricants. Indeed, it has always been necessary to ascertain by actual trial what liquids are suitable and what are not. Until the growth of the heavy mineral oil industry, almost all the lubricating oils and fats used were either of vegetable or animal origin, and engineers found by experience which particular oil or fat was suitable for any particular machine. Given the required lubricant, the proper running of the machine was guaranteed. But with the enormous growth of our industries depending upon machinery for their existence, the demand for lubricants became so great that the supply of vegetable and animal oils was not sufficient to meet the requirements, and the mineral oils were pressed into service whenever possible.

To ensure the use of suitable lubricants, the chemist had to be consulted. Although he could not ascertain by any chemical or physical tests whether a particular oil or fat was a good lubricant, he could say with some certainty whether a sample was genuine or adulterated, and knowing the kind of adulterant used, he could give useful advice to the purchaser. This was especially the case with animal and vegetable oils, but mineral oils could not be so satisfactorily dealt with.

The reason why one liquid should be a good lubricant and another not, has attracted a good deal of notice by physicists, chemists and engineers. Attention was first directed to viscosity; for it was found that the viscosity of the fluid was a very important consideration in lubrication problems. The exact part played by viscosity was made apparent by the experimental work of Beauchamp Tower and the theoretical consideration of his results by Osborne Reynolds. It appeared that when a liquid was applied to two surfaces in contact which were in relative motion, and certain conditions as to speed, &c., were fulfilled, that the oil became "trapped" between the surfaces and actually entirely separated them. The friction was then proportional to the mean thickness of the oil film, the rate of shear and the viscosity of the oil. This was a great step in advance, for it was apparent that any viscous liquid might act as a lubricant if such conditions were adopted as would ensure a proper film being formed. Engineers have not been slow to profit by the discoveries of Tower and Reynolds, for every care is now taken in the design of machinery to secure, wherever possible, the presence of a proper lubricating film.

The formation of a proper lubricating pad or film cannot, however, always be relied upon. At very low speeds and under very heavy loads such a film will not form, and the solid surfaces rub against each other. In other cases the lubricant is only held in position by capillary forces, and a film of sufficient thickness does not form. Indeed, there are many cases in which it seems impossible to form such a film. The slide valves of steam engines, the pistons of various kinds of engines and the slow moving pulleys of cranes are cases in point. Efficient lubrication then depends upon the liquid possessing some other property which enables it to

reduce the frictional resistance sufficiently. It thus came about that a true lubricating oil was regarded as a liquid possessing *oiliness*.

So far, it would appear that no satisfactory explanation has been given as to what oiliness really is. All that can be said is that some liquids of similar viscosity are not oily in this sense and will not act as lubricants.

Vegetable and animal lubricants are compounds of carbon, hydrogen and oxygen termed esters, formed by the union of alcohol radicles with fatty acid radicles. There are a great number of such fatty esters, several of which generally go to form each lubricant. The alcohol radicle occurring in the vegetable oils and in most of the animal oils is the trivalent radicle glyceryl C_3H_5 and its esters, known as glycerides, may be represented by the formula $C_3H_5R_3$, in which R represents the fatty acid radicle. Thus we have triglyceryl stearate, $C_3H_5(O.C_{18}H_{35}O)_3$; triglyceryl palmitate, $C_3H_5(O.C_{16}H_{71}O)_3$; triglyceryl oleate, $C_3H_5(O.C_{18}H_{33}O)_3$; and many others. Stearin and palmitin predominate in the solid fats, olein in the fluid oils. Olein is the chief constituent of many of the best known lubricants, such as lard, tallow, neatsfoot and olive oils. Allied to the fats are the waxes, which are esters of mono- and di-valent alcohols, and a few lubricants such as sperm oil belonging to this group.

Mineral lubricating oils are of entirely different chemical composition, consisting essentially of hydrocarbons, compounds of carbon and hydrogen, and we labour under the disadvantage of knowing little concerning their ultimate chemical structure. Dunstan and Thole,* however, have considered the peculiarities of these oils and conclude that all good lubricating mineral oils contain unsaturated molecules. They remark: "In no case has the chemical constitution of a component of a lubricating oil been established, but the chemical behaviour of these oils indicate that among the components are unsaturated hydrocarbons (possibly open-chain, but more probably naphthenic and polynuclear, or perhaps of both types), saturated hydrocarbons (naphthenic and probably to some extent polynuclear, but not to any appreciable extent paraffinoid), and aromatic hydrocarbons (to an unknown and possibly a limited extent) . . . . The

* "Journal" of the Institution of Petroleum Technologists, Vol. IV. (1918), pp. 191-228.

unsaturated compounds constitute between 20 and 40 per cent. of most lubricating oils . . . . It appears, then, that the true lubricant is an unsaturated compound, possessing all the attributes of such a compound, *i.e.* :—

(1) Capacity to absorb iodine, bromine, oxygen, and so on ;
(2) Solubility in strong sulphuric acid ;
(3) Higher C/H ratio than the saturated derivative.

" Apparently the same facts hold good in regard to fatty lubricants. Rape oil, castor oil and olive oil contain in their molecules double bonds, and are superior in body and viscosity to such a saturated product as, for example, tallow.

" In recent years the progress of organic chemistry has largely been due to the realisation that unsaturation, or the possession of residual affinity, plays an all-important part in the reactivity and the very personality of a compound. Colour, odour, taste, physiological activity, and, in a word, all the characteristic properties of bodies are influenced by this condition. It appears now that we may add lubricating ability to the already long list of effects proceeding from this one prime cause."

The relation of colloid chemistry to industrial problems has attracted much attention of late, and in regard to lubrication Dunstan and Thole remark " Recent work on colloid chemistry points to the fact that heavy oils must be included in the category of iso-colloids, *i.e.*, polyphase systems in which the disperse component is of the same chemical nature as the dispersion medium. Just as water must be regarded as a system in which molecules such as $(H_2O)_3$ co-exist with simple H_2O molecules, so in a lubricating oil the disperse phase is a molecular aggregate suspended in a dispersion medium of simpler and similar structure." They point out that the high viscosity, the large temperature-coefficient of viscosity and especially the hysteresis effects which have been observed in heavy oils are readily explained on this hypothesis. W. Ostwald* states that whenever a colloid comes in contact with a surface it fails to maintain a uniform special distribution. " On the surfaces of contact the concentration becomes different from that obtaining in the inner parts of

* " Introduction to Theoretical and Applied Colloid Chemistry " (1917), p. 87.

the colloid mass. . . . Usually the colloid tends to concentrate on the surfaces." This is known as *adsorption*, and the phenomenon was first pointed out by Willard Gibbs. Hardy, in a recent Paper,* has called special attention to this. He finds that with a true lubricant a film of the order of $1\mu\mu$ thickness is sufficient to cause two glass surfaces to slide over each other with the minimum friction, and concludes "that lubrication depends wholly upon the chemical constitution of a fluid," and that "the true lubricant is always a fluid which is adsorbed by the solid face. If this be so, then the problem of lubrication is merely a special problem of colloid physics."

That oiliness is not due to viscosity many experimental results show. In connection with the work of the Lubrication Committee of the Department of Scientific and Industrial Research, Messrs. Stanton and Hyde have made a large number of experiments on the friction of mineral and other lubricating oils with the Lanchester worm gear testing machine at the National Physical Laboratory. The results show conclusively that different mineral lubricating oils at the same viscosities give very different frictional results. The tests were made through a wide range of temperatures, and it was then possible to plot the results on a diagram having viscosities for abscissæ and ordinates friction. Fig. 1 shows one series of results obtained. It must be remembered that viscosity also affects the results here; but the property of oiliness shows itself strongly in the results.

It appeared to the writer that the property of oiliness might show itself most clearly when the two metallic surfaces were in actual contact, and that, therefore, valuable results might be given if the static coefficient of various oils between different metals were measured.

The friction experiments now to be described were made under conditions which insured that the surfaces should be in actual contact, and any differences in the frictional coefficients obtained with the oils tested must have resulted from the contact of the oily metals and not from the viscous flow of the liquid.

The experiments were made with a small hand-driven machine. Three pegs, each 5/32 in. diameter, rested upon the

* "A Problem in Lubrication." "Journal" of the Society of Chemical Industry, Vol. xxxviii. (1919), p. 7T.

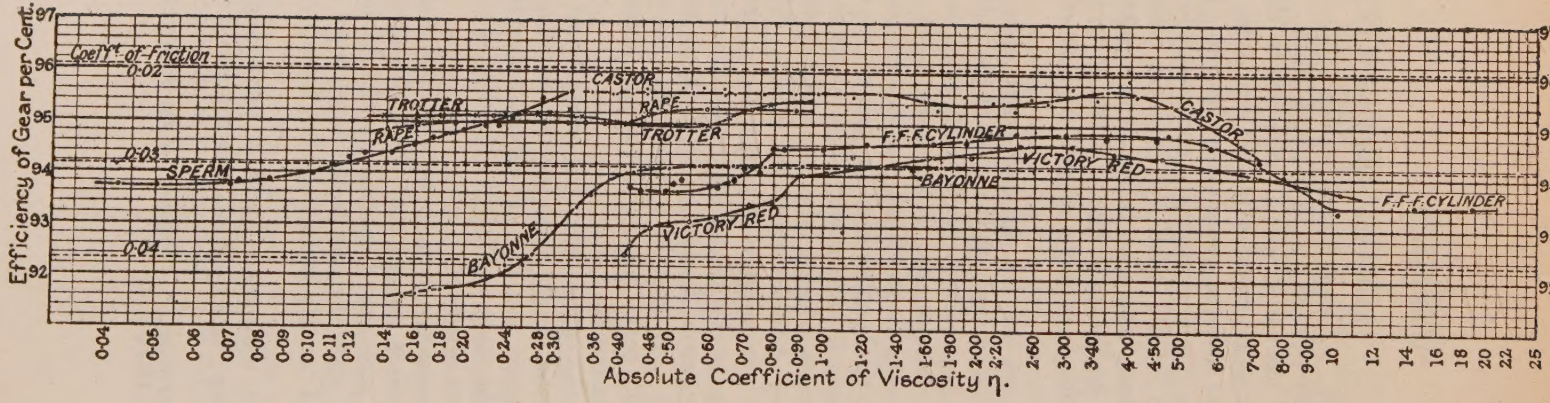
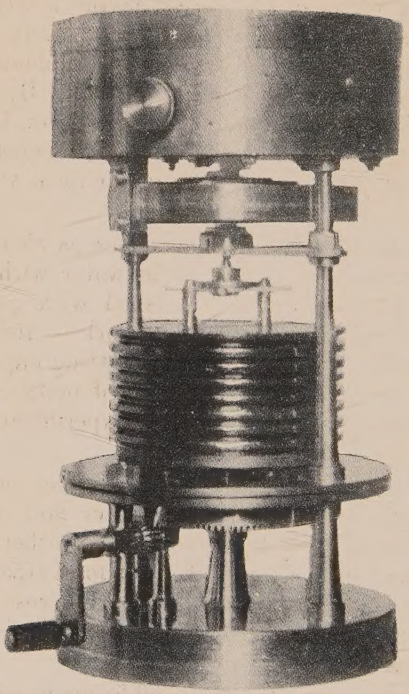


FIG. 1.—VARIATION OF EFFICIENCY OF WORM GEAR WITH VISCOSITY OF OIL.

Mean Distributed Load on Teeth of Gear = 1½ tons/sq. inch.
Mean Speed of Worm Shaft ... ... = 1080 revs./min.
Average Horse-Power Transmitted ... = 33½.



FRICTION TESTING MACHINE (DEELEY).

[*To face* p. 78.

flat surface of a disc of metal which could be slowly rotated. These pegs were secured, concentrically, to an upper disc which could be weighted as desired, and which actuated a spindle to which a spiral spring and recording finger were attached. When the lower disc was rotated, the pegs were carried with it by the friction until the surfaces slipped, owing to the stress on the spring, and the finger gave the value of the frictional resistance. To damp the oscillations of the finger, the spindle to which the finger and spring were attached was geared to a small train of wheels, the freely revolving end wheel of the series having a weighted rim to increase its inertia. A pawl and ratchet were also attached to the gear, to prevent the finger from suddenly falling back when the surfaces commenced to slip. By very slowly moving the driving handle the finger was soon brought to the position giving the static coefficient. The movable disc upon which the pegs rested lay in a circular dish, which could be filled with oil.

To insure clean surfaces, or surfaces as clean as possible, the rubbing metals were ground in water with flour of carborundum. They were then polished with fine wet emery cloth, rubbed well in water with a cork to remove as much emery as possible, dried with clean blotting paper, and finally well warmed to get rid of all traces of moisture. The temperature of the surfaces during the experiments varied from 16·0°C. to 18·0°C.

When the surface is thus prepared, and no lubricant is used, the static coefficient gets greater and greater as the surfaces continue to rub against each other. The initial static coefficient of a clean surface of mild steel resting upon cast iron was, in one instance, 0·154, and rose in the course of about 10 minutes to 0·417, and was still rising when the experiment was stopped.

A series of experiments was quickly made with surfaces of mild steel on cast iron, all quite clean. The results obtained are shown in Table I. The surfaces during each experiment were worked upon each other as little as possible, so as not to alter the conditions of their surfaces by wear.

Such clean surfaces are very sensitive to any contaminating agency. In one instance such a surface gave a momentary static coefficient of about 0·160. This surface was then

TABLE I.—*Clean Mild Steel upon Clean Cast Iron.*

Load per square inch. lbs.	Static coefficient of friction.	Kinetic coefficient of friction.
52·0	0·167	0·175
43·3	0·173	0·188
34·6	0·184	0·197
26·0	0·204	0·204
17·3	0·213	0·223
8·6	0·230	0·229

breathed upon for about 2 seconds, and a further test then gave a coefficient of about 0·452.

Each friction value given in the tables to follow is the mean of five determinations for each load of 52·0, 43·3, 34·6, 26·0 and 17·3 lb. per square inch respectively.

In the case of lubricated surfaces the procedure was as follows: As soon as the surface was clean and dry it was wetted with the lubricant to be tested, well rubbed with a cork to remove carborundum or emery, and then wiped clean with dry blotting paper. The surfaces were then worked in contact for a time, and the dark streak left on the disc was

TABLE II.—*Rape Oil with Mild Steel on Cast Iron. Surfaces Dry.*

Lbs. per square inch. lbs.	Coefficient of friction.
52·0	0·205
43·3	0·200
34·6	0·203
26·0	0·208
17·3	0·218
8·6	0·229

cleaned off with blotting paper and oil. The working of the surfaces together in this manner tended to smooth them, and it was found that the more this was done, with the surfaces dry but oily, the more nearly the static and kinetic friction approached each other in value. As the frictional value thus obtained varied with the extent to which the oil was rubbed off, no real value attaches to such figures; but the test was considered useful as it brought the rubbing surfaces into good condition. In Table II. some results obtained in this way are given.

The static and kinetic coefficients were practically the same.

Table III. shows the static coefficient of friction and the efficiencies obtained for a number of oils when tested between mild steel and cast iron, and between mild steel and a lead bronze alloy of the following composition :—

Copper	85·88
Tin	5·71
Lead	4·00
Zinc	4·19
Iron	0·10
Nickel	0·12
	100·00

The numbers representing efficiency were calculated by the following formula :—

$$100-(\text{static coefficient}\times 100)=\text{Efficiency}.$$

TABLE III.—*Surface Flooded with Oil.*

Description of oil.*		Mild steel on cast iron.		Mild steel on lead bronze.	
		Static coefficient.	Efficiency.	Static coefficient.	Efficiency.
HB. clock oil	M.	0·271	72·9	0·275	72·5
Bayonne oil	M.	0·213	78·7	0·234	76·6
Typewriter oil	M.	0·211	78·9	0·294	70·6
Victory Rod oil	M.	0·196	80·5	0·246	75·4
F.F.F. cylinder oil	M.	0·193	80·7	0·236	76·4
Manchester spindle oil.	M.	0·183	81·7	0·262	73·8
Castor oil	V.	0·183	84·7	0·159	83·1
Valvoline cylinder oil	B.	0·143	85·7	...	...
Sperm oil	A.	0·127	87·3	0·180	81·1
Trotter oil	A.	0·123	87·7	0·152	84·8
Olive oil	V.	0·119	88·1	0·196	80·4
Rape oil	V.	0·119	88·1	0·136	85·4

* A=animal oil; V=vegetable oil; M=mineral oil; B=blended oil.

There is a marked difference between the friction of the various oils when mild steel is opposed to cast iron and the copper alloy respectively. Rape and olive oil give the best results, and mineral oil the worst, castor coming between the mineral lubricants and the rest. Rape and olive oil are of equal friction-reducing value between mild steel and cast iron, but rape is the better oil between mild steel and the lead bronze.

It is interesting to note that the static coefficient of those oils which stand lowest on the list and have the smallest coefficients of friction are those which have proved in practice the best lubricants.

The value of the coefficient of static friction as a test for lubricants depends upon whether care has been taken to properly clean the surfaces in contact. It was found that unless the last traces of water were driven off by heating the results were unreliable.

The coefficients of friction given in Table III. make it clear that the static friction varies, not only with the lubricant used, but also with the metals in contact. Oiliness would appear to be an effect produced by the lubricant upon the metallic surfaces with which it is in contact, rather than a property dependent upon any particular physical property of the lubricant.

It would appear that the unsaturated molecules of the lubricant enter into a firm physico-chemical union with the metallic surfaces, thus forming a friction surface, which is a compound of oil and metal. This solid surface would also appear, in the case of metallic surfaces, to be much more than one molecule thick, the oil either penetrating some little distance into the metal, and altering its physical properties, or, as a result of abrasion, forming a paste of metal plus oil between surfaces covered by oil layers one molecule thick. Even when dry, such a surface differs remarkably from a clean metallic surface. When the contaminated skin of a metallic surface has been removed by a file, the teeth of the file cut the metal and remove it easily; but if such a clean surface of metal be slightly oiled, or even if the hand be rubbed over it, the file will not cut anything like so freely. Thin films of matter of this kind cannot be wiped off. It is necessary to grind the surfaces under water, or to cut off a thin layer. When a metallic surface is clean, water easily wets it, and the moisture may be readily removed by heating.

Clean metallic surfaces in frictional contact soon tear each other and heat; but when a lubricant is interposed it unites with the metals forming a solid, which is itself a lubricant. If this substance, oil plus metal, should be torn off the surface, fresh oil combines with the freshly exposed metal. In this way the metallic surfaces are prevented from touching and

seriously abrading each other. However, if the load be heavy, the heating resulting from the friction may be so great that the lubricant is destroyed, and the surfaces then seize and abrade each other.

Some experiments by Stanton and Hyde on the friction of mixtures of mineral oil with rape oil showed that a small proportion of rape oil had almost as marked an effect upon the friction as a much larger percentage. The rape oil, or a constituent of it, evidently displaced the mineral oil on the surfaces, and formed a rape oil plus metal film, which was as effective almost as if the surfaces had been in contact with pure rape oil.

Lubrication. *By* H. M. Martin, A.C.G.I.

Nothing of fundamental importance has been added to the theory of lubrication as it came from the hands of Osborne Reynolds in 1886. Sommerfeld made certain much needed improvements in the mathematical treatment of the cylindrical bearing, and even more valuable work, both from the theoretical and practical standpoints, was accomplished by Mr. A. G. M. Michell of Melbourne in 1905, who showed that it was possible to extend Osborne Reynolds' theory to bearings of finite dimensions, whereas both Osborne Reynolds and Sommerfeld had had to assume that the bearings they discussed were of infinite length; or alternatively that leakage of lubricant from the sides of the brass could be neglected. Mr. Michell showed that this assumption was far from being satisfied in practice.

From Osborne Reynolds' theory it appears that the law of comparison between bearings is that, under similar geometrical conditions, the load carried per inch *run* of a bearing (measured transverse to the direction of motion) is constant, being independent of the absolute dimensions of the bearing.

In short, if W be the load carried per inch run, its value is given by the relation

$$W = \frac{\lambda U}{c^2} \varphi$$

Here λ denotes the viscosity of the lubricant, U the relative velocity of the opposing surfaces, and c a geometrical co-

efficient, whilst φ is another co-efficient, the value of which varies with the amount of side leakage.

For a flat block of unlimited length (measured transverse to the direction of motion) the value of φ is .159, the viscosity pressure and velocity being taken in C.G.S. units. For a square block Michell has shown that the value of φ falls to .067. The writer has calculated that in this case about one-third of the lubricant escapes at the sides of the block and two-thirds at the trailing end.

It is thus evident that the assumption that side leakage can be neglected, as made by Osborne Reynolds and Sommerfeld, is materially in error.

Incidentally, it may be mentioned, in passing, that in the Michell Patent Extension case tried last March, evidence was given to the effect that the adoption of the Michell Thrust Block by the Navy had resulted in a saving to the nation of £600,000 during the years of the war.

Although, as appears from the foregoing, some of Osborne Reynolds' numerical co-efficients may require correction to bring them in to accord with actual practice, the present writer believes that on the physical side he left the theory of lubrication complete. Amongst his noteworthy applications of it was the explanation he was able to give of the slipperiness of ice.

Reynolds held that in all cases of lubrication, even imperfect lubrication, the opposing solid surfaces were separated by a film of the lubricant, which kept them from coming into physical contact.

The present writer thoroughly endorses this view; at any rate, so far as fluid lubricants are concerned.

As for solid lubricants, it would seem that no one has yet been able to suggest a "working model" to represent their action. It is, however, conceivable that this may be due, at least in part, to such lubricants reducing to a common level the inequalities of the opposing surfaces, and that the actual lubrication is then effected by some fluid.

Leaving this question aside, as in need of further investigation, the problem naturally arises as to how it is that certain fluids are recognised as good lubricants and others as bad ones. Under favourable conditions, indeed, any fluid will act as a lubricant. Mr. Michell has used molasses to lubricate sugar-making machinery. Mr. Ferranti had, so the writer is informed, some amount of success in the attempt to lubricate

spinning machinery with air, and water proves quite a satisfactory lubricant for the stern tubes of destroyers, the load carried being some 20 to 25 lb. per sq. in. of projected area, and the rubbing speed as much as 12ft. or 15ft. per second.

Nevertheless, as is well known, under conditions of imperfect lubrication some fluids prove satisfactory, and others entirely useless though credited with an equal or greater viscosity.

In a note contributed two or three years ago to the Committee on Lubricants and Lubrication, the present writer pointed out that in the case of imperfect lubrication the load was probably concentrated on a few " active " spots of limited area. A similar opinion had been expressed previously by Osborne Reynolds, who observed that under such conditions the friction would tend to be proportional to the load, which is not the case with well lubricated bearings.

If the load be thus concentrated the pressure in the oil film at the active spots will obviously be extremely high, and the writer accordingly suggested that under such conditions the viscosity of the lubricant might have a value very different from that obtaining at atmospheric pressure. He called attention to the work of Prof. Faust at Göttingen, who had found that the viscosity of such liquids as ether, carbon bisulphide and ethyl alcohol increased enormously as the pressure was raised from one to 3,000 atmospheres. He suggested accordingly that the Committee should find out whether anything similar occurred with lubricating oils. This suggestion was adopted, and the experiments made at the National Physical Laboratory, using for the purpose a very ingenious and simple apparatus devised by Dr. Stanton, and described by him at the recent meeting of the British Association.

These experiments did, in fact, show that at high pressures, the viscosity of oils was greatly increased. Had it turned out that this increase was higher with vegetable and animal than it was with mineral oils, some explanation of the property of " oiliness " might have been afforded. The reverse was, however, found to be the case, mineral oils showing a greater rise of viscosity with pressure than did animal and vegetable oils, and yet they are notoriously worse lubricants.

An explanation of this peculiarity must therefore be sought elsewhere.

Some 12 or 18 months ago Mr. R. M. Deeley informed the Lubrication Committee that he had found that good lubricants adhered much more firmly to metal surfaces than poor lubricants did. The present writer then suggested that under high rates of shear there might, with a bad lubricant, be slip at the boundaries of the oil film and the solid surfaces which it served to separate.

If this were the case lubrication would break down, as the moving journal would be unable to drag in the requisite supply of oil to maintain the film intact.

Some support for this view seems to be afforded by a remarkable experiment described by the late Lord Rayleigh in the "Phil. Mag." of January 1918. In this experiment a little carriage fitted with hemi-spherical feet of glass rested on a glass plate. The force required to produce sliding was measured under different conditions. With no lubricant, the surfaces being chemically clean, the resistance was high, whilst with a mere trace of lubricant probably approximating to a mono-molecular film, the resistance was remarkably low.

When, however, more lubricant was added so as to give a thick film, the resistance to sliding rose most markedly.

Now there is evidence that the attraction between a surface and the molecules of a mono-molecular layer of a liquid, is notably higher than the attraction between such a surface and a molecule of the liquid deeply buried under its fellows. For example, if a drop of oil be allowed to spread freely on water it will form ultimately a layer one molecule thick. If then the extent of the surface be decreased the excess of molecules, over and above those required to form a mono-molecular layer, gathers up into little lenses, the oil strives in fact to secure the largest possible extent of mono-molecular film . On this view, therefore, in Lord Rayleigh's experiment, the very thin layer of lubricant could withstand without slip a higher rate of shear, than could be sustained when the layer next the glass consisted of deeply buried molecules.

In practical cases of lubrication the rate of shear is often extremely high. The writer has calculated* that in turbine reduction gears, such as are used for ship propulsion, the thickness of the oil film separating the teeth is about $\frac{1}{8000}$ in., whilst the pressure in this film attains the value of some

* *See* "Engineering," August 11, 1916, p. 120.

3 tons per sq. in. This calculation was based on a load of 520 lb. per linear inch, uniformly distributed over the whole length of the gear. As more than one tooth is in engagement the load per linear inch of the tooth amounted to about 267 lb. In actual fact with rigidly mounted pinions an equal distribution of the load cannot be maintained. The torque alters the pitch of the helices, so that even if a perfect bearing from end to end of the teeth were secured at say, $\frac{1}{4}$ load, there would no longer be a uniform bearing at full load. As a matter of fact it is found that the surface of the teeth actually flows in service. The pressure, therefore, in the oil film must at times attain to 30 tons per sq. in., and the thickness must, when this flow takes place, be correspondingly very much less than the $\frac{1}{8000}$ in. calculated on the hypothesis of an equable distribution.

The sheer stress in the film must be exceedingly high. Under the hypothesis of uniform distribution of the load it comes out at 23 lb. per sq. in., and must be several times as great when the metal flows. Even when flow takes place lubrication is perfectly maintained. Indeed, Lord Rayleigh's experiment would seem to indicate, that lubrication is possible with films only a few molecules thick. In such cases the shear stress must be enormous, and there seems no inherent improbability that with bad lubricants slip does occur at the boundary between solid and fluid.

In the article "Atom," of the ninth edition of the Enc. Brit., Maxwell reports experiments in which slip was observed between the walls of a tube and a gas flowing through it. These experiments do not seem to have been confirmed, and no case has been reported of slip between a tube and a liquid. In none of the experiments, however, have the shearing stresses approached those which must occur in an imperfectly lubricated bearing.

In view of the fact now thoroughly established that metal will flow before seizure occurs it seems probable that in badly lubricated bearings, thoroughly run in, the load is concentrated on a narrow band of the brass, and not on a number of isolated spots as the writer formerly suggested. The initial irregularities in brass and journal will in fact tend to be levelled by the intense local pressures developed.

Molecular Layers in Lubrication. *By* H. S. Allen, *M.A., D.Sc., Physical Laboratory, The University, Edinburgh.*

In the "Notes on Lubrication," by Principal Skinner, and in the ensuing discussion ("Proc." Phys. Soc., Vol. 31, p. 94, 1919) emphasis was laid on the fact that under certain conditions vegetable and animal oils may be better lubricants than mineral oils. The best lubricants among the latter are those with a large proportion of unsaturated hydrocarbons. The property of oiliness is said to come in when there are regions of metallic contact. In this connection it may be of service to draw attention to the important work of Irving Langmuir on surface films ("Journ." Am. Chem. Soc., Vol. 38, p. 2221, 1916; Vol. 39, p. 1848, 1917). Adsorption of liquids or gases at the surface of a solid body is considered to be the result of unsaturated chemical forces at the surface. In many cases the adsorbed layer is only one molecule thick, and the conditions are determined by the shapes of the molecules and the relative activities of different portions of the molecules. The fact that animal and vegetable oils spread upon water whilst mineral oils do not, is explained by Langmuir as due to the presence of an "active group" in the molecule in the former case, and its absence in the latter. The soluble glycerine ester end of the rod-like molecule tends to dissolve in the water, but the insoluble hydrocarbon end refuses to do so, with the result that the molecule stands on end and the surface is covered with a layer of closely packed molecules of the animal or vegetable oil. On the other hand the mineral oils, with hydrocarbon groups at each end, refuse to spread. Similarly in the case of the adsorption of a liquid by a solid surface, when the molecules contain active groups, they will become oriented and will pack into the surface layer in much the same manner as in the case of oil films spread upon the surface of water. The application of Langmuir's theory to the case of lubrication is simple. In the extreme case we may picture each of the metallic surfaces covered with a layer of oil one molecule thick, resembling a piece of velvet firmly glued to the metal with the pile outwards. Two such velvet-clad surfaces can glide over one another with but little friction. Supposing that in some way actual metallic contact has been established, that oil will be most efficient which tends to spread over the metallic surfaces to form a lubricating layer. If the view

here suggested be correct the property of " oiliness " depends neither on the viscosity nor on the compressibility of the liquid in the first instance, but on the chemical forces called into play between the active part of the oil molecule and the solid surfaces of the bearing. Thus " oiliness " would depend not only on the nature of the lubricant but also on the nature of the solid surface with which the liquid is brought into contact.

Remarks submitted before the Meeting by PRINCIPAL S. SKINNER, *M.A.*

THE two main divisions of lubrication are :—

(1) Full lubrication with an abundant supply of the lubricant such as in an oil bath.

(2) With a limited supply as is obtained with an oil pad with a little oil on it.

In division (1) the physical property of the lubricant which determines the absorption of energy is the viscosity of the liquid. A cylindrical vessel, which contains a liquid in which hangs a coaxial cylinder supported on a torsion wire, forms a well-known laboratory apparatus for measuring viscosity. The outer cylinder is rotated, and a torque is exerted on the suspended cylinder through the viscosity of the liquid. We have only to suppose that the axis of the inner cylinder is moved parallel to itself towards the outer cylinder in order to arrive at an arrangement similar to a wheel working on a fixed axle. The displacement of the inner cylinder causes forces which tend to push it back. The resultant forces are what supports the weight in a machine. The forces were fully considered by Osborne Reynolds in his theory of lubrication. The forces may modify the properties of the fluid as it is known that increased pressure increases the viscosity, whilst the tensional forces may produce a stretching of the lubricant and ultimately a rupture in it. It is this last aspect of full lubrication that suggested the necessity of knowing exactly what went on inside a bearing. For this purpose glass bearings have been examined with results that I have described elsewhere.

Recently one of my students has made experiments with glycerine in a Lahmeyer oil tester. Here we have a fully

lubricated bearing. The torque is measured. As a result it was found that the torque obtained was of the order of that calculated from the viscosity. Special care was taken in these experiments to obtain the temperature of the lubricating film by means of a thermo-electric couple. This result bears out the view that viscosity is the important physical property in a fully lubricated machine.

Regarding division (2) lubrication with a limited supply of lubricant, we may trace the action of two solids rubbing on one another from the state of absolute cleanness to a state when there is a film of oil separating them. Some most interesting experiments have been made recently by Mr. W. B. Hardy and his son, and described and discussed in the " Philosophical Magazine " of July this year. These experiments, and their theory, may go far towards explaining the action of very thin films of oil. Briefly it appears that the clean glass surface of a watch-glass always seizes on a clean glass plate, however little the normal pressure between them. The watch-glass could not be displaced without tearing itself and the plate. When very thin films of liquids were used it was found that some liquids were inactive, whilst others promoted slipping and were lubricants. This division of liquids into active and inactive is an important discovery. The inactive liquids included water, alcohol, ether, whilst the active liquids included oils. With thick films all might be lubricants. As a result it appeared that oils in very thin layers could prevent seizing. It is only necessary, perhaps we may venture to say, to have the thinnest layer of active liquid to enable smooth metal surfaces to pass over one another freely. For lubrication with limited supply of lubricant we should, therefore, require a fluid that must readily form a film on the surface.

The theory briefly is that certain thin films will prevent the molecules constituting the surfaces from coming within their distance of cohesion, or from exerting cohesive attraction.

PROCEEDINGS AT THE MEETING.

PROF. C. H. LEES, F.R.S., President, in the Chair.

The PRESIDENT said they had met that evening to discuss the question of "Lubrication." The Council had thought that the time was opportune for such a discussion, and had accordingly called together engineers, physicists and chemists likely to be interested in it. They hoped to hear from the engineers what a lubricant ought to do and to be, and which were good lubricants and which were not; the physicists might be able to connect lubricating power with other physical properties of liquids, with viscosities, surface tensions and adsorptions; while the chemists might explain what was the connection between lubricating power and chemical composition of a lubricant.

Dr. T. E. STANTON, F.R.S., said that as the problem of lubrication tended to become more and more one for the organic chemist, he was afraid he was not a suitable person to open a discussion on that subject, but it might be of interest to the Society if he called attention to a few of the outstanding difficulties.

In the first place, they must realise that the work during the last 40 years had, to a large extent, been concerned with one case of lubrication —two lubricating surfaces in relative motion under moderate loads and with a limited supply of lubricant. Their practical knowledge of the laws of lubrication under these conditions was due mostly to Mr. Beauchamp Power. He had a half bearing and a 4 in. journal, and the lower part of the journal was always immersed in oil. His experiments ranged as regards loads from 100 lb. to 525 lb., and from 100 to 450 revs. per min. He found the frictional resistance fairly independent of the load and nearly proportional to the velocity, and that it always depended very considerably upon the temperature of the oil film. All these results were consistent with the assumption that the journal and shaft were separated by a film of oil, and on actually testing it Power discovered the existence of a film of oil under considerable pressure, and on measuring its intensity at different points he found that the total pressure was equal to the load.

After these results were published, the matter was taken up by Osborne Reynolds, who realised that this film might be thick enough for the unknown boundary conditions between the two surfaces to disappear, in which case the equations of hydro-dynamics could be applied to the motion. As the result of a somewhat laborious investigation he generally obtained an approximate solution for the half bearing. This theory showed that there must be essentially a difference of radii between the journal and the bearing, and that the point of nearest approach was on the off-side of the journal. The speaker illustrated this by reference to diagrams.

Reynolds also found when the distance between the surfaces was half the difference in radii, that then the pressure all through the film was everywhere greater than atmospheric pressure; and when the load exceeded the value corresponding to this condition, the pressure on one side became less than atmospheric pressure and the film tended to rupture.

This mathematical theory of lubrication was taken up by Sommerfeld, who had written a long Paper on the subject, pointing out several errors in calculation in Reynolds' Paper; also by Michell and by Harrison. Harrison's Paper was interesting because he had shown that when the bearing was treated as a complete cylinder an exact solution in two dimensions was obtained very easily.

An interesting fact brought out by Harrison's analysis was that the moment on the journal was not the same as the moment on the shaft, and on actually working the values out he found that taking that case of Reynolds, where the shortest distance between the bearing and shaft was half the difference of the radii, the ratio of the moment on the shaft to the moment on the journal was 1·5, which was disconcerting to those who, like the speaker, had to do tests of lubricants. To sum up for this particular case of lubrication his own opinion was that the theory had been so well worked out and the agreement between the observed facts and the calculated results was so good that more research was not needed.

It was the other case where the surfaces were so close together that the unknown boundary conditions were predominant that gave them trouble. As an instance of that he would take the case of a worm-gear transmitting high powers. In the case of the journal on the shaft, the oil film broke down at 120 lb. per square inch. Mr. Hyde in his experiments had found that in these worm gears, when they were transmitting 50 H.P., and the pressure between the teeth was of the order of 5 tons per square inch, they could get an efficiency over 97 per cent. He might call attention to those experiments Mr. Hyde had carried out, though he thought, perhaps, all the members of the Society were familiar with them. Mr. Hyde had tested a series of oils, animal, vegetable and mineral, in the worm-gear testing machines designed by Mr. Lanchester, and the results were interesting, but not easily explained. The speaker showed the results of a few of these in the form of a diagram, in which the values of the efficiencies obtained were plotted on a temperature base.

It was of interest to point out that the viscosity of the oils could have had no appreciable effect, for the reason that between temperatures of from 25°C. to 45°C. they could get no difference in efficiency worth mentioning, whereas in some cases the ratio of the viscosities was as great as 6 to 1. Perhaps one of the most interesting features of the tests was the effect of mixing a vegetable oil, such as rape oil, with mineral oils. It did not seem to matter whether they used 20, 15, 10 or 2½ per cent., they still obtained the same kind of effect, which consisted of a definite horizontal shift of the critical point through a range of temperature of about 20°C.

As regards the nature of the dependence of the efficiencies on the actual values of the viscosities, Mr. Hyde devoted a series of experi-

ments to that subject and found that the change of viscosity with the pressure was very large indeed, but still failed to throw any light on the peculiar behaviour of the oils in the worm-gear testing machine.

Mr. A. S. Barnes, who read Mr. R. M. Deeley's Paper (*see* pp. 1s to 11s), said that he was deputising that evening for the author, who was unfortunately not in sufficiently good health to be able to come and speak. Mr. Deeley began his Paper by reflecting that friction was both the friend and the enemy of engineers. There were many aspects of friction on which the engineer depended for use and assistance, but it was the hostile aspects of friction with which they were dealing that night, and those were countered or made as slight as possible by the use of lubricants.

Mr. J. H. Hyde gave a demonstration of Mr. Deeley's instrument. He said that Mr. Deeley's machine was designed to measure the static and kinetic coefficients of friction under various conditions of oiling. The metals could either be scantily lubricated or flooded with oil. Of the two metals to be tested together, one was in the form of a disc and the other in the form of three small pegs attached to a frame. In the lower part of the machine there was a shallow dish rotated by means of a small handle. Into this dish the metal disc and frame were placed, the latter such a way as to be free to rotate. On turning the small handle the three pegs were carried round against the torsion of a spring. The spindle of that spring was connected to a pointer through a train of wheels which provided a damping on the pointer. The wheel travelling at the highest velocity had a weighted rim to affect this.

Mr. Deeley had explained in his Paper that it was absolutely necessary to get rid of the contaminating film on the surfaces, so that it was found to be essential before consistent results could be obtained that both the disc and the three pegs should be ground under water. The greatest care must be observed that no oil, or even a contaminating film from the hands, should get on either surface before they were placed in position on the machine. On first putting the surfaces together and rotating the handle, the co-efficient of friction was usually fairly high, but on continuing to rotate them in oil the friction became higher and higher the longer the experiment was carried on. On pouring some oil in the dish and then beginning to rotate, the pointer was carried round until the slipping began to take place. The oil film was then formed between the surfaces and the pointer rushed back a considerable distance.

Mr. Hyde demonstrated the various parts of the mechanism.

Mr. Leonard Archbutt, F.I.C., F.C.S., said: In the consideration of lubrication problems it is necessary to make a very clear distinction between two prevailing conditions, viz. :—

(1) Those in which the solid surfaces are completely separated by a film of oil, such as occurs in the lubrication of cylindrical journals and their bearings, properly fitted, revolving at high speed and supplied with abundance of oil; and

(2) Those in which, owing to the shape or condition of the surfaces, the kind of motion, the high bearing pressure, low speed, or an inade-

quate supply of oil, the oil-film cannot form completely, or becomes broken, and the solid surfaces come into contact.

In (1) the friction is entirely due to the viscosity of the oil, as shown by Osborne Reynolds. Engineers have Reynolds' theory to guide them in the design of machines, and the chemist, by determining the physical and chemical characteristics of an oil, is able to give sound advice as to the suitability of any particular oil to meet the required conditions.

In (2), the circumstances are quite different. Oils alike in viscosity are found to have quite different friction-reducing values, and we have no knowledge to guide us in the selection of oils other than that gained by practical trial under working conditions. Experience has shown that mineral oils, as a rule, reduce friction less than animal and vegetable oils, why we do not know, though the great difference in the capillarity of the two kinds of oil is of importance. Of two mineral oils, or two fixed oils, alike in viscosity, one cannot say, without trial, which will give the lower friction. What we can say is, that under these conditions, *i.e.*, where solid friction comes in, viscosity alone is not the only or the most important factor, and that some other unknown property which we term "oiliness" is very important. An outstanding problem in lubrication is to determine the nature and cause of this property of "oiliness." Mr. Deeley's ingeniously designed machine seems likely to give us a valuable means of measuring oiliness, and his theory that oiliness is the property possessed by an oil, or a constituent of it, of combining with the surface to be lubricated and forming a lubricating film is, I think, in accordance with the theory of Irving Langmuir, of which Dr. Allen has given such a clear account. Dr. Allen says: "The application of Langmuir's theory to the case of lubrication is simple. In the extreme case we may picture each of the metallic surfaces covered with a layer of oil one molecule thick, resembling a piece of velvet firmly glued to the metal with the pile outwards." In a memorandum to the Lubricants Committee some time ago Mr. Deeley wrote: "I consider that the oil molecules which adhere to the metallic surfaces form part of the solid and that we have solid friction between such oily surfaces when they touch. . . . One comes to regard (lubricated) metallic friction surfaces as being of the nature of velvet pile rather than of unyielding material."

The importance of the friction surface is shown in the case of the white alloys known as "Anti-friction metals," and has long been familiar to engineers. In some recent tests of a mineral lubricating oil under conditions in which there was solid as well as viscous friction, I found that under the same conditions of speed and pressure, and with the same oil, bearings lined with white metal would carry double the load carried by bronze bearings without any increase of the friction. Prof. Goodman many years ago noticed that the presence of traces of bismuth and other metals had a great effect in modifying the friction of a white metal surface. He found that if the added metal had a smaller atomic volume than the white alloy the friction was increased, but if it had a greater atomic volume the friction was diminished.

On Dr. Langmuir's theory the molecule of the oil and of the surface are held together by residual or secondary valence, and the more chemically active the lubricant the more firmly it will be attached. Mr.

Southcombe's discovery of the importance of the free fatty acid in lubricating oils is, therefore, of great interest. Hitherto, free acid of any kind in a lubricant for metallic surfaces has been regarded as a constituent to be avoided, and for very good reasons. In steam cylinders, in lubricating greases containing water, and even in lubricating oils containing no more moisture than that due to natural causes, fatty acids attack the metal surfaces forming metallic soaps which obstruct steam passages and dissolve in and thicken the lubricant, besides damaging the metallic surfaces themselves, but Mr. Southcombe has shown that fatty acids in very restricted amount are an advantage, as they improve the lubricating value of a mineral oil to the same extent as a much larger quantity of fatty oil would do. Here, again, it is necessary to be quite clear as to the conditions under which the fatty acid is advantageous. In condition (1), where the friction is entirely due to the viscosity of the oil, the fatty acid is of no advantage. It is in condition (2), where solid friction occurs, that its presence is useful. The effect is very marked and very remarkable. In some experiments made with a Thurston machine under conditions of low speed and fairly high bearing pressure—7 ft. per minute and 270 lb. per square inch—I have found that 1 per cent. of rape oil fatty acid added to a mineral lubricating oil reduced the coefficient of friction from 0·0047 to 0·0035. Two per cent. of fatty acid did not reduce the coefficient to a lower figure. Neutral rape oil added to the mineral oil also reduced the friction, but 60 per cent. of the neutral oil was required to give as low a friction coefficient as 1 per cent. of the free fatty acid. Perfectly neutral rape oil is not, of course, a commercial article, perhaps fortunately. All commercial rape oil contains free fatty acid and, consequently, much less is required than if it were neutral, but the important fact is that a very small percentage of fatty acid added to a mineral lubricating oil improves the lubricating value of the mineral oil as much as a much larger percentage of fatty oil and leads to considerable saving in the cost of oil, as well as other advantages. It is important to note, however, the fact that I have found perfectly neutral rape oil to give a lower friction than a mineral oil of the same viscosity and that the presence of free fatty acid in rape oil does not seem to reduce the friction nearly so much as rape oil fatty acid added to mineral lubricating oil reduces the friction of the mineral oil.

I have made comparative tests with commercial rape oil containing 2·4 per cent. of free fatty acid, perfectly neutral rape oil prepared from the same rape oil, and a mineral oil of very nearly the same viscosity at the temperature of the tests. I found that the neutral rape oil gave a much lower friction than the mineral oil, the acid rape oil gave a somewhat lower friction than the neutral rape oil. The figures obtained were :—

Mineral oil (900/7)	0·0078
Rape oil, neutral	0·0050
Rape oil, 2·4 per cent. free acid	0·0045

If these results are confirmed, say, by careful tests on Mr. Deeley's machine, it appears that the oiliness or lubricating efficiency of the unsaturated molecules of the neutral rape oil is nearly as great as that of the free fatty acid molecules, but that in their influence on the hydro-

carbon molecules of the mineral oil the acid molecules are much more active. The size of the molecules and the thickness of the molecular layer will have an important influence.

Langmuir's Papers will, no doubt, be carefully studied by physical chemists. They appear likely to throw very considerable light upon this subject.

In a communication, received by the Secretary on December 4, 1919, Mr. Archbutt wrote that since the meeting he had read the Paper by Mr. W. B. Hardy and Flight-Lieut. J. K. Hardy in the " Phil. Mag." of July, 1919, in which their theory of static friction and lubrication is very fully and clearly discussed. He thought this important Paper should be read in connection with the present discussion. It was interesting to note from the table of " threshold values," on page 44, of Messrs. Hardy's Paper that between glass and glass oleic acid gave the same low friction as castor oil. He agreed that it was essential to experiment with individual chemical substances in investigating the theory of lubricants, but it was also necessary to experiment with commercial lubricants acting between such dissimilar metals as are used in the construction of machines, in order to obtain the information which engineers required to guide them in the lubrication of machinery. He looked forward with great interest to further Papers on this subject from Mr. Hardy and his son.

Principal S. Skinner said he would to some extent depart from the synopsis of his printed remarks, just noting that he had divided lubrication into two parts, the full lubrication on the one hand, and the very thin film on the other. With regard to the first division, he was going back to an old subject, *i.e.*, the cavitation in a fully lubricated bearing. He was having constructed a bearing and journal with a good fit, and was hoping to show the rupture that he had observed with a similar piece of apparatus in which the fit was not so good. He felt that it was certain that viscosity was the chief property which a fully lubricated bearing had to fight against, still it was of interest to see as far as possible what was exactly going on in a bearing. He had a slide in the lantern which showed the cavitation. (The speaker here showed his slide). He would like to mention that the tensile strength of fluids had been the subject of some careful experiments by Max Toepler, who had studied the rupture of liquids in an apparatus consisting of a lens oscillating on a glass plate.

The second division of lubrication which he gave, referred chiefly to Mr. Hardy's experiments with very thin films, to which should be added the views and experiments of Langmuir. In connection with films against solids he had noticed recently an interesting letter in " Nature " from Mr. Twyman, who asked whether anyone had noted the change of the refractive index in liquids against a surface. He might congratulate himself on the synopsis of his printed remarks, since it agreed largely with what had been said already by other speakers.

Mr. W. B. Hardy, F.R.S., said that he had attempted to reduce the problem to its simplest elements by avoiding purely mechanical complication and by the use of undivided chemical substances as lubricants.

The influence of chemical constitution upon lubrication cannot be traced by the study of mixtures. It is impossible to assign to any particular substance an absolute value as lubricant. For instance, water is an anti-lubricant for glass, a feeble lubricant for bismuth and an admirable lubricant for ebonite. Acetic acid and tripropylamene are admirable lubricants for glass and only feeble lubricants for bismuth. Lubrication is due to the interaction of two substances at a surface. The property known as "oiliness" is due to the influence of the lubricant upon the surface energy of the solid. It is to be expected, therefore, that lubrication can be defined only in terms of the chemical constitution of the lubricant *and* of the solid to which it is applied.

The study of a large number of chemical individuals proves that the influence of chemical constitution is complex beyond expectation. The only generalisation to which no exception has yet been found is that the introduction of a *single* hydroxyl group into a molecule increases its action as a lubricant. A second and a third hydroxyl group, however, diminish lubricating value. In general the single hydroxyl group is very much more effective attached to a ring or closed chain nucleus than to an open chain nucleus.

The worst lubricants are simple symmetrical compounds, such as benzine and carbon tetrachloride. Putting H in place of Cl, or CH_3 in place of H increases lubrication. There is no particular virtue in unsaturation. In simple compounds, such as paraffins, it slightly increases lubrication. In other cases it may decrease lubrication. In most chemical series lubrication increases as the molecular weight increases, according to a law which may be exponential or linear. In some series it decreases as molecular weight increases. An example is the simple aliphatic esters.

The most striking result is that lubrication has no particular relation to the fluidity of the lubricant. Thus in the fatty acid series or paraffins the curve connecting lubricating power with molecular weight shows no deviation where the substances change from fluids to solids at the temperature of observation. It must be remembered that these experiments deal with static friction, but it is not possible to avoid incidental observations upon the simplest case of kinetic friction. They support the view that the fluid state has no particular value in kinetic friction as such and apart from purely mechanical factors.

The above conclusions are from experiments with bismuth sliding on bismuth. They will not hold for glass on glass. For instance, the hydroxyl group does not always increase lubrication, and it is almost without influence compared to the carboxyl group, when the solid is glass.

Professor F. G. Donnan said that he was at present engaged upon investigation of the optical analysis, by means of measurements of the double refraction produced, of the strain and rate of relaxation of strain in lubricating oils and other liquids and mixtures of liquids subjected to high rotational shear. He quite agreed as to the importance of the surface-energy factor, but it appeared to him that in a complete theory of lubrication this other aspect of the problem might be of equally great importance.

Mr. J. E. Southcombe said he was sure the discussion they had had that evening had been most inspiring, and they were agreed definitely over two points; first, that there were two distinct types of lubricating phenomena, one in which the mechanical phenomena were dealt with, and those in which they got low speeds and high pressures, and in which the truly physical aspects were the more important.

Being somewhat of an enthusiast on the subject of "oiliness," it was particularly interesting to him to find the meeting was so unanimous in considering that "oiliness" was something very distinct, and a very important phenomenon in the practice of lubrication. It was this phenomenon which Mr. Wells and he commenced to investigate some years ago. They were primarily interested in trying to distinguish wherein fatty oil differed as a lubricant from mineral oil. The considerable superiority of the fatty oils over the mineral oils—the pure hydro-carbon oils—was very important in some types of machinery.

The first thing that would obviously appear as an essential qualification of a lubricant was that it should wet the surface. He would like to draw attention to a bearing and a journal in a condition of rotation which was slightly eccentric. Suppose they put in between two surfaces some mercury. In that case they would get a meniscus. The effect of that meniscus was to draw the liquid out in the directions of less constriction. The definition of a lubricant was that it was a substance which should flow into the regions of higher pressure. If, instead of mercury, oil were put in that space between the two surfaces, a meniscus of a different form would be obtained. In the first case the ends of the meniscus were directed outward, and in the second case they were directed inward, and by capillary laws the tendency was for the liquid to move into the more restricted areas of high pressure. The vital condition of lubrication, therefore, was surface tension.

There was a further point. Let them consider the rise of liquid in a capillary tube. If the distance of constriction was less than the normal capillary rise, it followed that the oil would tend to lift the journal, and would extend itself. It would be true to regard water as a lubricant if there were always a pure, clean surface, but not in the case of a contaminated or greasy surface. The water meniscus in a greasy bearing would be the other way round.

Having recognised that that peculiar capillary phenomenon seemed to be the most important thing in lubrication, attention must be directed to getting some sort of measure of the capillarity of oils, to see whether they could distinguish some property in the fatty oil not possessed by the mineral oil, since density and viscosity and compressibility did not give a measure of lubricating value.

To make a long story short, they seemed to find themselves forced to the conclusion that there was some phenomenon which remained to be investigated with regard to surface tension. Instead of employing the old methods in investigating surface tension, they were endeavouring to determine the surface tension of oils against another liquid, in one case water. The speaker described on the blackboard his experiments with a pipette filled with oil, and showed the results obtained with mineral oils, and then with certain fatty oils, including olive oil, cocoanut oil, lard, and a series of others. In the case of the mineral oils, the results in the pipette were of the order of 98 to 102 drop num-

bers, and in the case of the fatty oils were of the order of round about 150, or of a totally different order to the drop numbers obtained in the case of the mineral oil. They had, therefore, at once some distinguishing characteristic between the fatty oil and the mineral oil. Ultimately those values of that variation of the drop number were shown to rise from the presence of fatty acids. Recently, Prof. Lewis had repeated that experimental work and determined the capillarity of oils against mercury surface.

It remained to ask what exactly the *modus operandi* was in the practical case of lubrication. He did not find himself at all in agreement with Mr. Hardy when he said that the problem of lubrication should be considered on pure surfaces and surfaces free from all disturbing influences; because it was the disturbing influence or the contaminating effect that was of importance above all others in practical lubrication. When it came to be considered, oil was only rarely used under ideal conditions. In nine out of ten cases, water was splashing about and metallic particles, dirt, dust, oxides and so on were present. The greatest problem with those of them who were oil manufacturers was to make an oil that would emulsify with water for a certain job and for another job would not emulsify with water—in other words, to deal with the contaminating effect.

If they considered a brass surface in practical use, a little reflection would show that it was not a brass surface; it was a surface of metallic brass coated with some contaminating agency. If there was a film of moisture on that brass surface and they placed upon it a drop of oil, *the oil, supposing it contained a fatty acid, would have a lower interfacial tension and would tend to spread.* A film of metallic oxide on that bearing surface would behave similarly. In one sense that brought them to Langmuir's view. They must agree that where there was a tendency for chemical action, the surface tension necessarily became lower. If they had an inert hydro-carbon oil on such a surface, it had no chemical affinity in any sense whatever for the journal.

He did not propose to discuss that evening the number of details as to the practical application to known cases. The hypothesis had been worked out on a friction machine and in practice with most conclusive results. There was, of course, a further reason which supported the conclusion, viz., the adsorption layer. If they had between journal and bearing a pure hydro-carbon, there could be no possibility of adsorption. There must be a third substance capable of adsorption by the bearing surface.

Mr. E. Edser said that during the last few years he had been engaged in an industry of a most romantic character. It was concerned with the recovery of minerals from rocks. A rock might contain about 1 per cent. of copper in the form of sulphide, and the problem was to recover that copper. Under ordinary conditions the cost of getting it out of the rock would be greater than the worth of the substance. It was necessary to concentrate the copper to more than 10 or 15 per cent. That was done by grinding up the rock fairly finely so that it passed a screen of 60 to 80 mesh, then mixing it with water containing small quantities of oil or other substances, and then agitating the mixture violently. The result was that the mineral rose to the surface

in a froth. Some of the small bubbles obtained were so persistent that they could be pressed between two microscope slides and on release would assume their original forms.

There were a multitude of problems in connection with that subject, none of them particularly difficult in itself. It was essential to learn under what conditions a particle would adhere to a bubble. A few years ago there was a good deal of literature published on that subject, especially in the United States, and all manner of effects were described and theories proposed. He wanted to point out that although flotation did not seem to have any connection with lubrication, it would probably be discovered on further investigation that a connection existed. There was this peculiar fact to reckon with, that the substances which oil adhered to, water would not adhere to. A substance seemed to have "affinity" either for water or for oil, but not for both. It seemed to him that the problem of lubrication involved the adhesion of oil to a shaft or to a bearing. An attempt to run a steel shaft in a steel bearing produced unsatisfactory results; different substances must almost invariably be used for the shaft on the one hand, and for the bearing on the other.

He would like to mention a point which was seldom given sufficient prominence, viz., that a surface layer of any substance whatever, solid or liquid was less dense than the interior of that substance.

The speaker illustrated on the blackboard his conception of the attraction and repulsion of molecules, and said that it was easy enough to imagine how oils and such like substances could become entangled in the surface layers of solids. In this connection he would like to mention an experiment performed by Clerk Maxwell, about 1870, in a lecture at the Royal Institution. He took a sheet of glass and a lens and measured the force exerted between them, finding that in order to get optical contact one must be pressed against the other with considerable force, and that on removing the force the lens moved away from the glass to a distance comparable with the wave-length of light. It was a significant fact that when two flat surfaces of glass were placed together the black spot indicating optical contact was never obtained, although the surfaces when left pressed against each other ultimately adhered and could not be separated.

Perhaps this phenomenon was due to the surface layer of a solid being in a comparatively rarified condition, somewhat resembling a gas; the surface layer of a liquid had been proved by Van der Waals to have the character described and there should be no essential difference between the surface layer of a solid and that of a liquid. It would be remembered that Beilby had proved that the surface layer of a solid was fluid and by gently rubbing a copper surface with chamois leather, films had been formed over small pits in the surface.

When two perfectly plane surfaces were placed "in contact" there appeared to be almost perfect freedom of motion of one over the other, which again suggested the rarefaction of the surface layers. A drop of water between the surfaces destroyed the freedom of motion, and a drop of oil did the same. This indicated the difficulties encountered in explaining lubrication; it is practically impossible to obtain effective lubrication between two perfectly flat surfaces. This fact was emphasised by Osborne Reynolds in his explanation of lubrication.

The PRESIDENT said he thought on the whole they had learned more about how the different liquids stood with regard to "oiliness" than about the reason one liquid was a good and another a bad lubricant. When he came there he hoped that some theory of adsorption such as that of Langmuir was going to offer a good explanation of all the facts, but that hope had been disappointed owing to the new facts brought forward by Mr. Hardy.

They had to thank the various speakers who had taken part in the discussion and the Secretary, Dr. Owen, who had organised the discussion so well.

COMMUNICATED REMARKS.

Mr. A. E. BERRIMAN, Chief Engineer, Daimler Company: It has been made quite clear that there are two principal states of lubrication, which, for convenience of reference, may be called A and B; state A being the condition in which an intermediate stream of oil entirely separates the bearing surfaces; state B being the condition in which the bearing surfaces are apparently in solid contact.

From the engineering standpoint, state A is ordinarily associated with bearing pressures that do not exceed about 400 lb. per square inch, although higher values may be maintained in this state by special means under suitable conditions. State A has no coefficient of friction, since the friction under practical loads is sensibly independent of the load, but varies as the bearing area and the square root of the speed.

State B has a coefficient of friction, which experiments with the Lanchester machines show to be in the order of 0·025. It is distinguished from state A by this fact and also by the fact that wear does take place even in ideal conditions. The validity of regarding state B as a lubricated state depends on the fact that this wear does not destroy the surface nor does it generate more heat than the system can dissipate. In fine, it is a stable state.

The present discussion is an attempt to elucidate the physical condition of state B, and there are two principal theories under consideration. The Deeley theory contends that the metal surface is chemically contaminated by the action of the oil, so that a new solid compound is formed on the surface. The Martin theory contends that the metal is not chemically affected, but that good lubricants adhere to the surface in ultimate films.

It is to be observed that in both the Martin and the Deeley theories the phenomena are related to layers of monomolecular thickness, but in the one case the partial failure of lubrication is attributed to the tearing away of the contaminated metallic surface and in the other to a slipping of the ultimate oil film, as a prelude to metallic contact.

So far as the practical results are concerned, it matters perhaps little to the engineer what theory is proved to be correct; but it is of very first-class importance that the problem should be solved in such a manner as to provide engineering science with the data needed to ensure the successful operation of those moving parts that must, by their very nature, operate in state B.

The most that I, as an engineer, can contribute to the discussion is to recapitulate some of the practical phenomena bearing on the subject.

It is, for instance, common knowledge in engineering that certain materials are more difficult to lubricate effectively than others because they tend to score and seize more readily, but this does not in itself give the key to the reason.

It has also been well established that the bearing pressure in state B lubrication may attain a value at which the metal will flow, and yet changing the oil will cause a change in the coefficient of friction.

Yet another phenomenon is that a perfectly made plug gauge can be moved readily in a perfectly made ring gauge, if the surfaces are lubricated and the motion is maintained, but seizure will take place if the relative motion ceases.

Of these examples, the first two might be explained by either theory, but perhaps more readily by Deeley's than Martin's. The last-mentioned example of the plug and ring gauge, however, seems to be capable of explanation more readily by Martin's theory than Deeley's, because in this case there has been no physical abrasion to remove the chemical compound from the surface, and the quality of its friction should not be dependent upon a state of motion as appears, in this instance, to be the case.

The significant difference that takes place when the state of motion changes to a state of rest in this experiment suggests that oiliness is related to surface tension.

F. W. Lanchester, M.Inst.C.E.: During the time I have been actively engaged in engineering work, at least as far back as 1889, I have been acquainted with the fact that the lubricating properties of an oil depend upon factors other than viscosity; I believe that the millwrights and engineers of last century were as a class fully alive to the same fact. It is to be recalled that when mineral oils were first introduced and offered as lubricants such oils were not well received by the practical men of the day, and for a long while they were a drug on the market at a price far below that of other oils of similar "body."

My own experience carries me to a date a few years later than the publication of Prof. Osborne Reynolds' Paper on "The Theory of Lubrication." One of the results of that Paper was undoubtedly to throw discredit on the opinions of the practical man of that period, and to cause the alleged superiority of animal and vegetable oils to be regarded as moonshine. A secondary consequence was that about that period also mineral oils began to obtain wide acceptance as substitutes for animal and vegetable oils more or less implicitly on the results of viscosity tests. A contributory factor to the ready acceptance of mineral oils was, of course, the advent and general use of the internal combustion engine, for which most of the lubricants previously used were unsuitable.

My own experience, however, as to the inferiority of mineral oils, about 1890, was quite decisive. I found myself in charge of the test bench at a works manufacturing gas engines, and it was my invariable practice, if a bearing ran hot when first on test, to substitute castor oil for the mineral oil usually employed, when all difficulty at once vanished. The large end connecting rod bearing in particular was frequently doped in this manner. I tried other oils, including mineral oils of equivalent viscosity, but castor oil invariably gave the best results. This and

other experience left no doubt whatever in my mind that there was a property of *oiliness* inherent to a greater or lesser extent in good lubricants that could not be accounted for by the ordinary physical properties or tests. I am quite sure also that this remained the view of the older hands and practical men of that date.

My worm-gear testing dynamometer was designed and built at the Daimler Works and was first put to work in 1912. This dynamometer gives readings that are estimated to be within one-tenth of 1 per cent. of the truth, and must be regarded, of its class, as an instrument of very high accuracy. The immediate result demonstrated was, of course, the high efficiency obtainable by a worm gear of good design, but the trials also brought out in a startling manner peculiarities in the properties of the lubricants employed. Not only did two oils of the same, or nearly the same, viscosity often give entirely different readings, such, for example, as a mineral oil in which the coefficient of friction might be nearly double that of an animal or vegetable oil, but the curves given by different oils were so characteristic that with a little experience it was almost possible to say what oil was used from an inspection of the plottings of the efficiency readings. It was quite evident at once that, compared to any previous oil-testing appliance, such as Thurston's machine, the new dynamometer possessed properties of an altogether higher order of merit.

Without giving or attempting a quantitative definition of *oiliness*, it is certain that qualitative differences may be recognised with certainty between different oils by aid of the worm-gear dynamometer. In truth, after working with this machine and having had through my hands the results of a great many tests and experiments, I was led to state that the lubricating properties of an oil for worm gear could no more be judged by its viscosity than the brew of beer or vintage of champagne. Thus the following two conclusions are given ("Proceedings" of the Institution of Automobile Engineers, Session 1912-13, Vol. VII.):—

1. That in general mineral oils are inferior to animal or vegetable oils.
2. That the viscosity of the oil is little or no guide in the selection of an oil for the purpose in question*; one might as well try and judge the merits of beer or any other beverage by the viscosimeter.

I am sure that to-day it is impossible to dispute the existence of a property of *oiliness* apart from the ordinary physical properties of a lubricant and, so far as this view is only of recent acceptance amongst scientific men, so far we may take the period from 1886 until to-day as a measure of the time it has taken to recover from an overdose of Osborne Reynolds. I have, of course, nothing to say against the work of Osborne Reynolds; his Paper or something equivalent was necessary to the scientific theory of lubrication, but I well remember the time when, mainly, I think, in consequence of his Paper, the old practical worker of last century, whether engineer or millwright, was looked upon as an ignorant and prejudiced person, and when those who shared his view were liable to be stigmatised as charlatans and quacks.

The fact is, that although Osborne Reynolds' Paper on "The Theory of Lubrication" is the truth and nothing but the truth, at least we may take it as such, it is certainly not the whole truth. It would, I think,

* Worm gear lubrication.

be well to qualify it by referring to it as " The Theory of the Thick Oil Film in Lubrication." The whole question of the thin oil film and the conditions of lubrication pertaining to same, one might say an entire world of lubrication, is ignored. The conditions of lubrication as between gear teeth, whether it be spur-gear or worm-gear, in no way come within the scope of Mr. Osborne Reynolds' investigation, and moreover, the ordinary journal bearing is more dependent upon the oiliness of the lubricant than might be inferred. In the event of a journal bearing not being well bedded in the first instance the thin film lubrication and the oiliness of the lubricant are of paramount importance until, if we may so express it, the Osborne Reynolds' condition is established. The same applies in the event of a journal bearing becoming out of truth either from an accidental cause or ill-treatment.

It must not be forgotten, however, that a great deal of knowledge of the behaviour of lubricants existed before Mr. Beauchamp Towers' experiments or Mr Osborne Reynolds' Paper thereon. Some physicists have, perhaps, a tendency to assume ignorance on the part of those who do not read Papers before Scientific Societies. Knowledge and the expression of knowledge are two entirely different things, and the one very commonly exists long before the other. I think there is no doubt that the engineers of 1850 and thereabouts understood perfectly well that it was necessary to maintain a *film* of oil or lubricant and that the thickness of the oil (which was later termed viscosity) was one of the factors which determined the suitability of an oil for its purpose. It is not easy to find explicit references, but Rankine, writing a decade or more before Osborne Reynolds' Paper, says :—

" Three results in the preceding Table, No. 16, 17 and 18, have reference to smooth firm surfaces of any kind, greased or lubricated to such an extent that the friction depends chiefly on the continued supply of unguent and not sensibly on the nature of the solid surfaces ; and this ought almost always to be the case with machinery. Unguents should be thick for heavy pressures that they may resist being forced out and thin for light pressures that their viscidity may not add to the resistance."

Generally speaking, the writers of the older works on engineering took the question of lubrication for granted. It is rarely, if ever, for example, that in the index the word " oil " or " lubrication " finds any place, and one may more often than not search for a drawing or figure of such a thing as a lubricator in vain. However, references are found to the " oil film," showing that this essential conception of what we may describe as the unit of lubrication had been clearly formulated.

The various explanations given in the present discussion as to what in fact constitutes the property of oiliness have, of course, an interest quite apart from and beyond the mere establishment of the fact itself. If oiliness were a physical property one cannot but feel that it ought to be capable of definition and able to be expressed in terms of the dimensions L M.T. ; it is, however, clearly by no means necessary that it should be a physical property. When under examination by a recent Committee (Institution of Mechanical Engineers) I expressed the view that the unknown property might possibly be due to the mechanical destruction of the oil by attrition, as, for example, as though the oil

were decomposed, gasified or partially gasified by local heat; in such a case the actual lubricant might be microscopic bubbles of gas or a gaseous film, in other words—the oiliness might possibly not be due to the oil at all but to its products of dissociation. This was only put up as a suggestion and not as an opinion, my idea being that in the investigation of oiliness our minds must be kept open very wide, even to include a possibility so remote.

In many of the explanations put before the meeting the chemistry of the lubricant is being made the pivot of investigation and the suggestion of the saturation or non-saturation of the molecule is shown as a possible or probable factor of importance. The chemistry of the subject is not much in my line, but I do feel that the investigation should be encouraged and every hopeful channel should be thoroughly explored. If a reasonably complete theory of the lubricating property of lubricants can be developed we may be on the way to obtain lubricants of vastly greater potentiality than anything with which we are now acquainted; perhaps, for instance, lubricants that will enable machines to be worked at really high temperatures. Even should investigations only lead us to the more economic and appropriate use of those lubricants we at present know, the total money saving and financial value the world over would be incalculable.

R. S. Willows, M.A., D.Sc.: Most theories of lubrication have concerned themselves chiefly with the physical properties of the lubricant, such as the viscosity. I think a successful theory must take into account certain molecular effects which, by some workers, are classed as chemical, but which I prefer to regard as physical, although I doubt whether there is any reason for differentiating between the two classes of forces. The present note is a contribution to that end.

One point to be explained is how the lubricant maintains a continuous film between the two rubbing surfaces. This is really the fundamental question why some liquids wet a given solid, while others fail to do so. A theory which has been advanced from different standpoints by Thomson ("Phil. Mag.," May, 1914) and Langmuir ("Jour. Amer. Chem. Soc.," 1917, *et. seq.*) goes some way towards a solution and has a great amount of evidence in its favour from other directions. In certain molecules some of the atoms are supposed to have lost and others to have gained one or more electrons (Thomson); hence these molecules will exhibit the properties of electrical doublets, and will be surrounded by a strong electrical field. Thomson shows, from measurements of dielectric constants, that certain chemical groups, like OH, COOH, &c., are especially marked in this respect. The cohesion of a liquid then arises, in part at all events, from the atttractions between such doublets; surface tension and viscosity are other manifestations of the same effect. To extend this to metals: It is well known that the electrons in metals are in a state of considerable freedom, hence when a liquid whose molecules possess fields of force comes near a metal it may have the power to bind certain of the electrons from the metal, so creating an electrical double layer, whose negative portion is near or in the oil. We have, in fact, what is usually called adsorption taking place. (If the molecular aggregates in the metal also possess a field the effect will be enhanced.) With such an

arrangement considerable cohesive forces between solid and liquid will be called into play; at the same time, and owing to similar causes, the viscosity of the oil will be large. Thus two of the main characters of a good lubricant—adhesion to the solid and high viscosity—can be accounted for, and such friction as there is will be between the adsorbed layer and those liquid layers near it. Langmuir's theory contemplates similar forces, although he does not state explicitly how they arise. Because they are localised in certain directions he classes them as chemical—in view of modern physics, not a very convincing argument—and ascribes them to secondary valencies—a name which does not make the matter clearer, at least, to a physicist. He has, however, shown by some strikingly beautiful experiments that the presence of such groups as OH, &c., does cause one liquid to spread over another, and has made some remarkable deductions concerning the shapes of certain molecules. Hardy has shown that a pure hydro-carbon oil does not spread on water, while an impure one spreads rapidly; while in a discussion on a Paper by Skinner last session it was stated that a saturated hydro-carbon is a poor lubricant, but its lubricating properties are greatly improved by the presence of unsaturated hydro-carbons. These facts are consistent with the theory given above, since, from the data given by Thomson and Langmuir, the saturated molecules will have weak fields of forces. It also explains the fact that animal and vegetable oils are better lubricants than those of mineral origin, since unsaturated molecules are more likely to be present. It would be interesting to know if the non-spreading property of a pure hydro-carbon oil is affected by heat owing to possible molecular changes causing doublets, and if the viscosities of a non-spreading and of a spreading oil differ appreciably. Perhaps Mr. Hardy can give us this information.

Experiments of the following type might also be useful. (1) Immerse a weighted quantity of powdered bearing metal in a good lubricating oil, then centrifuge strongly and weigh again, thus obtaining the weight (and thickness ?) of the adherent layer. Repeat with a non-lubricating but equally viscous liquid and so determine whether the adsorption is very different in the two cases. (2) The cohesion of a liquid can be determined by O. Reynolds' method. Theoretically it should be greater under a strong electric field, if Thomson's doublets are present, for they will align themselves under the action of the field, and neighbouring molecules will attract each other. Similar considerations would perhaps lead us to expect that good lubricating liquids should have high dielectric constants.

When molecules possess long chains, Langmuir shows that the non-active part of the molecule is turned from the interface water-compound when a thin layer of the compound spreads over the water surface; the other molecules of the compound will then have little attraction for the adsorbed layer, since they can approach only the inactive ends of the molecules in this layer. If such conditions occur in a lubricant we should have an adherent layer on the solid and reduced friction against the next liquid layer. This would ensure good lubrication, and the slipping between the liquid layers might be abnormally easy where the total thickness is only a few molecules.

VII. *First Steps in the Experimental Analysis of a Galvanic Cell.* *By* Prof. W. M. Coleman.

Received April 8, 1919.

First, to test the effects of changes of pressure in a galvanic cell upon the current it yields, I designed the following apparatus :—

A glass tube 3 cm. in diameter was used for the cell ; it was about 40 cm. in length, and one end was drawn down to a diameter of 4 mm. The cell was made inverted, and wires from the lower ends of the zinc and copper plates were led out at the bottom through a perforated rubber stopper.

A piece of rubber tubing was placed on the small upper end of the tubular cell, and the battery fluid was introduced by means of partial exhaustion with jet pumps.

The rubber tube was then connected with a bicycle pump, and the pressure was raised 240 mm. Hg., as shown by a manometer ; or it was lowered by about one-fourth of an atmosphere by connecting with a jet pump.

It was found that slowly raising or lowering the pressure seldom caused variation in current ; but a sudden rise of about 240 mm. Hg. caused the current to increase about 5 milliamperes, and a like decrease brought an equal decrease in current strength (shown by an average decrease in reading of 5 milliamperes)—from 65 to 60 milliamperes.

A rise of pressure of 240 mm. Hg. caused a slight fall in potential, a fall being noticeable in the scale of the D'Arsonval galvometer at each stroke of the pump, the total movement of the indicator amounting to three marks on the scale (equivalent, perhaps, to one-hundredth of a volt).

My next test was to find whether any effect would result from varying the pressure inversely between the zinc and copper plates. For this test I dissected the cell, and placed an element at each end of a glass tube 3 cm. in diameter and 2 metres long. Tests were made with this tubular cell held in a horizontal position ; also in the vertical position with copper and zinc ends alternately down. With a cell 2 metres long the change in hydrostatic pressure on reversing the ends was a little more than one-fifth of an atmosphere. The current increased about 2 milliamperes (the readings were 4 and 6 milliamperes) when the zinc end was suddenly turned down ; and it decreased when the tube was reversed.

In the above tests with the dissected cell, as well as those with the undissected but inverted cell, the absence of change in current when the pressure was changed slowly and gradually, and the changes in current with sudden changes of pressure indicate that the results are due to changes in polarisation by dislodgment of gas, and that they were not due to direct effect of changes of pressure upon the chemical action.

I expect to repeat the tests of potential already given, and to use a quadrant electrometer instead of a galvanometer.

I wish to acknowledge with thanks the assistance of Mr. W. H. Hayle, of the Cavendish Laboratory, in the foregoing experiments. I wish especially to thank Sir J. J. Thomson for the privilege of using the laboratory.

ABSTRACT.

When the pressure in a galvanic cell is suddenly varied, the current in the external circuit is altered, an increase in pressure increasing the current, and vice versa. When the pressure in the neighbourhood of the zinc electrode is suddenly increased, and that in the neighbourhood of the copper electrode is diminished at the same time, an increase in current takes place, and vice versa.

VIII. *Radiation from a Perfectly Diffusing Circular Disc. (Part I.)*

By JOHN W. T. WALSH, *M.A. (Oxon), M.Sc. (Lond.). (From the National Physical Laboratory).*

RECEIVED OCTOBER 30, 1919.

Synopsis.—When investigating the light emission from the positive craters of arcs, especially of the large ones of modern design, it becomes of importance to know what percentage of the total light is obscured by the negative carbon, particularly when the lamp is burning at a short arc length, which may be a fraction of the diameter of the positive carbon.

It is generally assumed that the positive crater radiates as if it were a perfectly diffusing circular disc, *i.e.*, a disc the radiation from which, in any direction, is proportional to the cosine of the angle between that direction and the normal to the surface.

To a first approximation it may next be assumed that the negative carbon acts as a second circular disc coaxial with the positive crater, and at a distance from it equal to the arc length.

On this assumption it is easy to find the proportion of the total light which is obstructed by the negative and this may be done either (i.) by deducing the required result from Sumpner's theory of the whitened sphere, or (ii.) by calculation from first principles.

The first method is shorter ; but the second has been added here as it serves to introduce a method which leads to a closer approximation to the actual conditions of the problem, viz., the light obscured by an infinitely long negative carbon.

It will be seen that the results given have a wider application than that for which they were obtained, as the problem of determining the illumination at any point of a disc by a second coaxial perfectly diffusing disc is one of considerable interest in photometry. The amount of light received by a searchlight mirror from the positive crater of an arc also follows at once. The illumination at any point in the penumbra produced by a disc shading a coaxial radiating disc, can also be calculated. This is shown in a second part of the Paper.

Dr. Sumpner* has shown that if the interior of a sphere consist of a perfectly diffusing surface (*i.e.*, a surface radiating

* Physical Society, "Proc." XII., 1892, p. 10.

according to the cosine law), then the flux from any element of the surface of the sphere is equally distributed over the remainder of the surface

Now suppose a diffusing plane surface be introduced into the sphere, as at AB in the figure. It is known that the radiation to any point from this surface will be the same as that from the segment of the sphere, ACB, which it encloses, for if the intrinsic brilliancy of the two surfaces be the same, their brightnesses viewed from any point will be equal.

Hence it follows that a plane circular surface AB, uniformly bright, produces a uniform illumination over the surface of any sphere of which its edge forms a small circle.

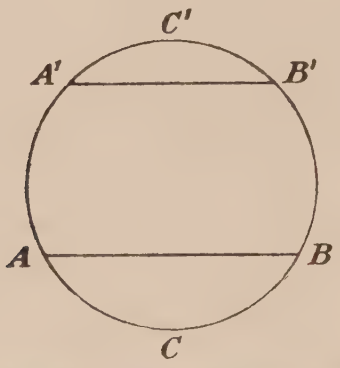


FIG. 1.—PRINCIPAL SECTION OF RADIATING SPHERE AND DISCS AB, $A'B'$.

Thus the proportion of the total flux from AB which is received by a parallel disc $A'B'$ is equal to the ratio of the spherical area $A'B'C'$ to the whole spherical area $AA'C'B'B$.

Now if m is the radius of the sphere, a the distance between AB and $A'B'$,

$$2r = A'B'$$

$$2R = AB.$$

Then $$a = \sqrt{m^2 - r^2} + \sqrt{m^2 - R^2}.$$

Also, spherical area $A'C'B' = 2\pi m(m - \sqrt{m^2 - r^2})$.

Spherical area $AA'C'B'B = 2\pi m(m + \sqrt{m^2 - R^2})$.

Total flux emitted from AB is $\pi R^2 \ \pi\Phi$, where Φ is the flux emitted in the normal direction per unit area.

$$\therefore \quad \text{Flux received by } A'B' \text{ is } \frac{m-\sqrt{m^2-r^2}}{m+\sqrt{m^2-R^2}}\pi^2R^2\Phi$$

$$=\frac{\pi^2\Phi}{2}[(a^2+r^2+R^2)-\sqrt{(a^2+r^2+R^2)^2-4r^2R^2}].$$

It is clear from what has been said above that the same amount of flux will be received by any disc of the same radius as $A'B'$ placed so that its edge forms a small circle of the surface $AA'C'B'B$.

The results obtained above can also be deduced from first principles as follows :—

Let A be an element of a perfectly diffusing surface (*i.e.*, a surface which radiates according to the cosine law), so that if the flux radiated normally be Φ per unit area. the flux

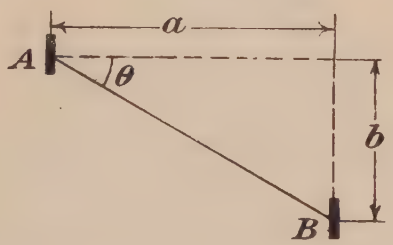


FIG. 2.—FLUX RECEIVED FROM RADIATING ELEMENT A BY A PARALLEL ELEMENT B.

radiated in a direction making an angle θ with the normal is $\Phi \cos\theta$ per unit area.

If now B be an element of a surface parallel to A and at a normal distance a from it, then if the line AB make an angle θ with the normal at A, the intensity of the radiation falling on B from A is given by

$$\frac{A(\Phi \cos\theta)}{a^2\sec^2\theta}.$$

Hence the flux received by B from A is

$$\frac{A\Phi\cos\theta}{a^2\sec^2\theta} \cdot B\cos\theta = \frac{A.B.\Phi}{a^2}\cos^4\theta.$$

(I.) From this result it is easy to find *the flux received from a radiating disc by an elementary area parallel and coaxial with it.* For the flux received by B from the radiating disc is (*see* Fig. 3), if R be the radius of the disc,

$$\frac{B\Phi}{a^2}\int_0^R \cos^4\theta \,.\, 2\pi b \,.\, db \quad (\text{where } b = a\tan\theta)$$

$$= 2\pi B\Phi \int_0^{\tan^{-1}R/a} \cos\theta \sin\theta d\theta.$$

$$= \pi B\Phi R^2/(R^2+a^2)^*.$$

Note.—Similarly it may be shown that the flux received by the whole of a disc of radius r from an elementary radiating

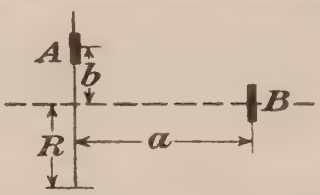


Fig. 3.—Flux Received from Radiating Disc of Radius R by a Parallel and Coaxial Element B.

area A parallel and coaxial with it at a distance a is equal to

$$\pi A\,\Phi r^2/(r^2+a^2).$$

Since the total radiation from the element is $\pi A\,\Phi$ (obtained by putting r infinite compared with a), the fraction of the whole which falls on the disc is $r^2/(r^2+a^2)$.

(II.) The above result can now be used to find *the flux received from a radiating disc by an elementary area parallel with it but at a distance* ρ *from the axis.* For let PQS (Fig. 4) be the radiating disc of radius R, and let its centre be C, and the projection upon its plane of the elementary area, O. Let $OC = \rho$ and let OPQ be drawn cutting the circle in P and Q so that the angle $COQ = \alpha$.

The values of OP and OQ are given by the expression

$$\rho\cos\alpha \mp \sqrt{R^2 - \rho^2\sin^2\alpha}.$$

Now the flux reaching the elementary area from the area $PQQ'P'$ of the disc (where $QOQ' = d\alpha$) is the difference between that reaching it from a sector OQQ' and that from a sector

* This expression was obtained by E. P. Hyde, "Bull." Bureau of Standards, 1907, III., p. 88.

OPP', *i.e.*, it is, from the result of section (I.), if B be the area of the element,

$$\frac{d\alpha}{2\pi}(\pi B\Phi)\left\{\frac{OQ^2}{OQ^2+a^2}-\frac{OP^2}{OP^2+a^2}\right\}$$

Hence the total flux received from the whole disc is

$$\frac{B\Phi}{2}\int_{\sin^{-1}-R/\rho}^{\sin^{-1}R/\rho}\frac{4a^2\rho\cos\alpha\sqrt{R^2-\rho^2\sin^2\alpha}}{(a^2+R^2+\rho^2\cos 2\alpha)^2-4\rho^2\cos^2\alpha(R^2-\rho^2\sin^2\alpha)}d\alpha.$$

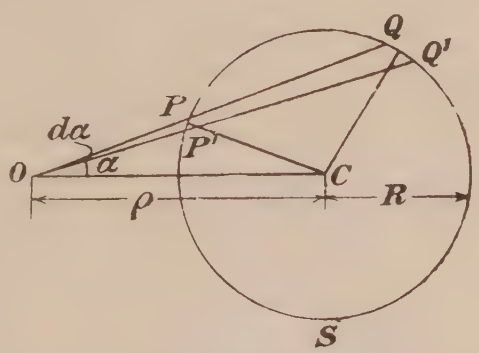


FIG. 4.—FLUX RECEIVED FROM RADIATING DISC PQS BY A PARALLEL BUT NON-COAXIAL ELEMENT WHOSE PROJECTION ON THE PLANE OF PQS IS O.

Putting $(R^2-\rho^2\sin^2\alpha)=x^2$ and writing c for $(a^2-R^2+\rho^2)/2a$, this becomes

$$B\Phi\int_0^R\frac{x^2dx}{(c^2+x^2)\sqrt{R^2-x^2}}$$

$$=B\Phi\left[\sin^{-1}\frac{x}{R}\right]_0^R-\frac{B\Phi c}{\sqrt{c^2+R^2}}\left[\cos^{-1}\frac{c}{R}\sqrt{\frac{R^2-x^2}{c^2+x^2}}\right]_0^R$$

$$=\frac{\pi B\Phi}{2}\left[1-\frac{c}{\sqrt{c^2+R^2}}\right].$$

Hence the radiation received is

$$\frac{\pi B\Phi}{2}\left\{1-\frac{c}{\sqrt{c^2+R^2}}\right\}^* \quad \text{where } c\equiv(a^2-R^2+\rho^2)/2a.$$

* This expression was obtained by P. D. Foote, "Bull." Bureau of Standards, XII., 1916, p. 585.

NOTE.—Similarly it may be shown that the flux received by a disc of radius r from an elementary area parallel with it but at a distance ρ from its axis is given by

$$\frac{\pi A\Phi}{2}\left\{1-\frac{c'}{\sqrt{c'^2+r^2}}\right\}, \text{ where } c'\equiv(a^2-r^2+\rho^2)/2a.$$

Since the total radiation from the area is $\pi A\Phi$ (obtained by putting r infinite compared with a and ρ), the fraction of the whole flux from the area which falls on the disc is given by

$$\frac{1}{2}\left\{1-\frac{c'}{\sqrt{c'^2+r^2}}\right\}.$$

(III.) Finally, *the flux received by a disc from a radiating coaxial disc* is obtained from (II.) by integrating over the circle whose radius is r. Hence the required expression is

$$\frac{\pi\Phi}{2}\int_0^r\left\{1-\frac{a^2-R^2+\rho^2}{\sqrt{(a^2+R^2+\rho^2)^2-4\rho^2R^2}}\right\}2\pi\rho d\rho.$$

Putting $x\equiv(a^2-R^2+\rho^2)$ this becomes

$$\frac{\pi^2\Phi}{2}\int_{\rho=0}^{\rho=r}\left\{1-\frac{x}{\sqrt{x^2+4a^2R^2}}\right\}dx$$

$$=\tfrac{1}{2}\pi^2\Phi[(R^2+r^2+a^2)-\sqrt{(R^2+r^2+a^2)^2-4r^2R^2}].$$

Hence the flux received by a disc of radius r from a coaxial radiating disc of radius R at a distance, a, from it is

$$\tfrac{1}{2}\pi^2\Phi[(R^2+r^2+a^2)-\sqrt{(R^2+r^2+a^2)^2-4r^2R^2}].$$

Since the total radiation from the disc of radius R is $\pi^2\Phi R^2$ (obtained by putting r infinite compared with a and R), the fraction of the whole flux from the disc which falls on the disc of radius r is

$$[(R^2+r^2+a^2)-\sqrt{(R^2+r^2+a^2)^2-4r^2R^2}]/2R^2.$$

Since this expression is symmetrical with respect to r and R, clearly one disc receives from a second coaxial disc the same amount of flux that the second disc would receive from the first.

The following applications of the foregoing expressions are of interest.

(IV.) For a given radiating disc, to find the surface traced out by the edges of coaxial discs receiving equal amounts of flux from it.

Let the given amount of flux be Q.

Then $Q=\frac{1}{2}\pi^2\Phi[(R^2+r^2+a^2)-\sqrt{(R^2+r^2+a^2)^2-4r^2R^2}]$

Hence the equation to a principal section of the required surface is

$$(R^2+x^2+y^2)-\sqrt{(R^2+x^2+y^2)^2-4x^2R^2}=2Q/\pi^2\Phi=K^2, \text{ say,}$$

if the axis of the discs and a radius of the radiating disc be taken as axes of y and x respectively. This reduces to

$$(R^2+x^2+y^2)^2-4x^2R^2=(R^2+x^2+y^2-K^2)^2,$$

i.e., $$x^2(4R^2-2K^2)-2K^2y^2+K^2(K^2-2R^2)=0.$$

But $$K^2=2Q/\pi^2\Phi \text{ and } Q<\pi^2\Phi R^2.$$

$$\therefore \quad K^2<2R^2.$$

Hence the principal section is an hyperbola—*i.e.*, the surface required is an hyperboloid of revolution, about the common axis of the discs, the equation to the principal section being

$$(2x^2-K^2)(2R^2-K^2)-2K^2y^2=0,$$

where $$K^2\equiv 2Q/\pi^2\Phi.$$

Any two discs parallel with the radiating disc and bounded by this surface will receive the same amount of flux, so that any zone (or any portion of a zone, by symmetry) of this surface must receive equal amounts of flux on both sides, for the flux passing *in* must balance that passing *out* through any part of the surface.

(V.) To find the amount of flux received from a radiating disc by an element of any sphere of which the edge of the disc forms a small circle.

If m be the radius of the sphere,

$$a=\sqrt{m^2+r^2}+\sqrt{m^2-R^2}.$$

$$a^2+r^2+R^2=2m^2+2\sqrt{(m^2-r^2)(m^2-R^2)}$$

The flux received per unit area by a zone of the sphere, parallel with the disc and at a distance a from it, is (Fig. 5)

$$\frac{\pi^2\Phi}{4\pi m}\frac{d}{da}[(R^2+r^2+a^2)-\sqrt{(R^2+r^2+a^2)^2-4r^2R^2}]$$

$$=\frac{\pi^2\Phi}{2\pi m}\cdot\frac{d}{da}[R^2+a(\sqrt{m^2-R^2}-m)]$$

$$=\pi\Phi[\sqrt{m^2-R^2}-m]/2m$$

which is independent of a, and therefore constant over the sphere. [This is the result obtained from first principles by Dr. Sumpner (*loc. cit.*).]

(VI.) It is clear that if O be the projection of an element of the radiating disc on the plane of the base of the cylinder PTQ, the flux received from O by the walls of the cylinder will be equal to that received by the area bounded by the two tangents from O to the circle and the portion of the circumference convex to O.

This equals, as in section (II.),

$$\frac{A\Phi}{2}\int_{\sin^{-1}-r/\rho}^{\sin^{-1}r/\rho}\frac{OP^2}{OP^2+a^2}da$$

$$=\frac{A\Phi}{2}\int_0^{\sin^{-1}r/\rho}\left[\left(\frac{OQ^2}{OQ^2+a^2}+\frac{OP^2}{OP^2+a^2}\right)-\left(\frac{OQ^2}{OQ^2+a^2}-\frac{OP^2}{OP^2+a^2}\right)\right]da.$$

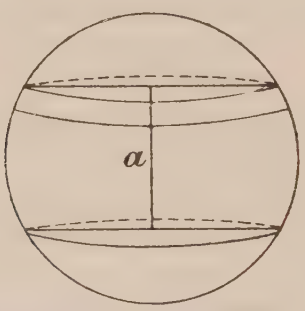


FIG. 5.—FLUX RECEIVED PER UNIT AREA BY A ZONE OF THE SPHERE OF WHICH THE RADIATING DISC FORMS A SMALL CIRCLE.

The second half of this integral has already been evaluated in section (II.) as

$$\frac{\pi A\Phi}{4}\left\{1-\frac{a^2+\rho^2-r^2}{\sqrt{(a^2+\rho^2-r^2)^2-4\rho^2r^2}}\right\}.$$

The first half

$$=\frac{A\Phi}{2}\int_0^{\sin^{-1}r/\rho}\left\{\frac{a^2(OP^2+OQ^2)+2OP^2OQ^2}{(OQ^2+a^2)(OP^2+a^2)}\right\}da$$

$$=\frac{A\Phi}{2}\int_0^{\sin^{-1}r/\rho}\left[1+\frac{t^4-a^4}{(t^2-a^2)^2+4a^2\rho^2\cos^2\alpha}\right]da.$$

Putting $(t^2-a^2)\tan a=x$, this becomes

$$\frac{A\Phi}{2}[a]_0^{\sin^{-1}r/\rho}+\frac{e\Phi}{2}(t^2+a^2)\int_{a=0}^{a=\tan^{-1}r/t}\frac{dx}{x^2+(t^2-a^2)^2+4a^2\rho^2}$$

$$=\frac{A\Phi}{2}\left[\sin^{-1}\frac{r}{\rho}+\frac{(t^2+a^2)}{\sqrt{4a^2\rho^2+(t^2-a^2)^2}}\tan^{-1}\frac{r(t^2-a^2)}{t\sqrt{4a^2\rho^2+(t^2-a^2)^2}}\right].$$

Hence the flux received by the walls from the whole radiating disc is equal to

$$\frac{\Phi}{2}\int_r^R 2\pi\rho\sin^{-1}\frac{r}{\rho}d\rho+\frac{\Phi}{2}\int_r^R\frac{2\pi\rho(t^2+a^2)}{\sqrt{4a^2\rho^2+(t^2-a^2)^2}}\tan^{-1}\frac{r(t^2-a^2)}{\sqrt{4a^2\rho^2+(t^2-a^2)^2}}d\rho$$

$$-\frac{\Phi}{2}\int^R\pi^2\rho\left\{1-\frac{a^2+\rho^2-r^2}{\sqrt{(a^2+\rho^2-r^2)^2-4r^2\rho^2}}\right\}d\rho.$$

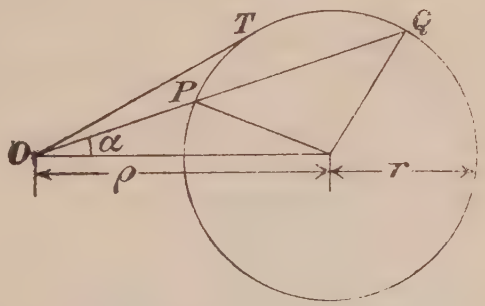


FIG. 6.—FLUX RECEIVED FROM A RADIATING DISC BY THE WALLS OF A CYLINDER INFINITELY LONG IN ONE DIRECTION.

The first integral

$$=\frac{\pi\Phi}{2}\left[R^2\operatorname{cosec}^{-1}\frac{R}{r}-\frac{\pi r^2}{2}+\sqrt{R^2r^2-r^4}\right].$$

The second integral (since $\rho^2=r^2+t^2$, so that $\rho d\rho=tdt$) becomes

$$\pi\Phi\int_{\rho=r}^{\rho=R}\frac{t^2+a^2}{\sqrt{(t^2+a^2)^2+4a^2r^2}}\tan^{-1}\frac{r(t^2-a^2)}{t\sqrt{(t^2+a^2)^2+4a^2r^2}}tdt.$$

Integrating by parts and putting $y \equiv \sqrt{(a^2+t^2)^2+4a^2r^2}$, we have that this

$$= \frac{\pi\Phi}{2}\left[y \tan^{-1}\frac{r(t^2-a^2)}{ty} \right]_0^{\sqrt{R^2-r^2}} - \frac{r\pi\Phi}{2}\int_{\rho=r}^{\rho=R} \frac{y^2-2t^2(t^2-a^2)}{(r^2+t^2)(a^2+t^2)}\,dt$$

$$= \frac{\pi\Phi}{2}\left[y \tan^{-1}\frac{r(t^2-a^2)}{ty} - (a^2+r^2)\tan^{-1}\frac{t}{r} - 4ar\tan^{-1}\frac{t}{a} + rt \right]_0^{\sqrt{R^2-r^2}}$$

$$= \frac{\pi\Phi}{2}\left[\sqrt{(R^2+r^2+a^2)^2-4r^2R^2}\,\tan^{-1}\frac{r(R^2-r^2-a^2)}{\sqrt{(R^2-r^2)\{(R^2+r^2+a^2)^2-4r^2R^2\}}} \right.$$

$$+ \frac{\pi}{2}a\sqrt{a^2+4r^2} - (a^2+r^2)\tan^{-1}\sqrt{\frac{R^2}{r^2}-1}$$

$$\left. - 4ar\tan^{-1}\frac{\sqrt{R^2-r^2}}{a} + r\sqrt{R^2-r^2} \right].$$

The third integral

$$= \frac{\pi^2\Phi}{4}\int_r^R \left\{ 1 - \frac{a^2+\rho^2-r^2}{\sqrt{(a^2+\rho^2+r^2)^2-4r^2\rho^2}} \right\} d\rho^2.$$

This equals, as in section III.,

$$\tfrac{1}{4}\pi^2\Phi[(R^2-r^2)+a\sqrt{a^2+4r^2}-\sqrt{(a^2+r^2+R^2)^2-4r^2R^2}]$$

Thus, the total amount of flux received *by the walls* is

$$\frac{\pi\Phi}{2}\left[\frac{\pi Q}{2} + Q\tan^{-1}\frac{r(R^2-r^2-a^2)}{Q\sqrt{R^2-r^2}} + 2r\sqrt{R^2-r^2} \right.$$

$$\left. - (a^2+r^2+R^2)\tan^{-1}\frac{\sqrt{R^2-r^2}}{r} - 4ar\tan^{-1}\frac{\sqrt{R^2-r^2}}{a} \right],$$

where $$Q \equiv \sqrt{(a^2+r^2+R^2)^2-4r^2R^2}.$$

As an example of the practical application of the formulæ given above, it is of interest to take the case of a carbon arc of diameter D with negatives of diameters $(0{\cdot}4)D$, $(0{\cdot}5)D$, $(0{\cdot}6)D$, and $(0{\cdot}7)D$. The proportion of light obscured by a "disc" negative of these dimensions at various arc lengths is easily calculable from the formula of section (III.), and the results are shown in graphical form in Fig. 7.

The extra light obscured by the stem of the negative in two particular cases has been calculated from the formula of section (VI.). For a negative whose diameter is half that of the positive, the obscuration of the stem of the negative is

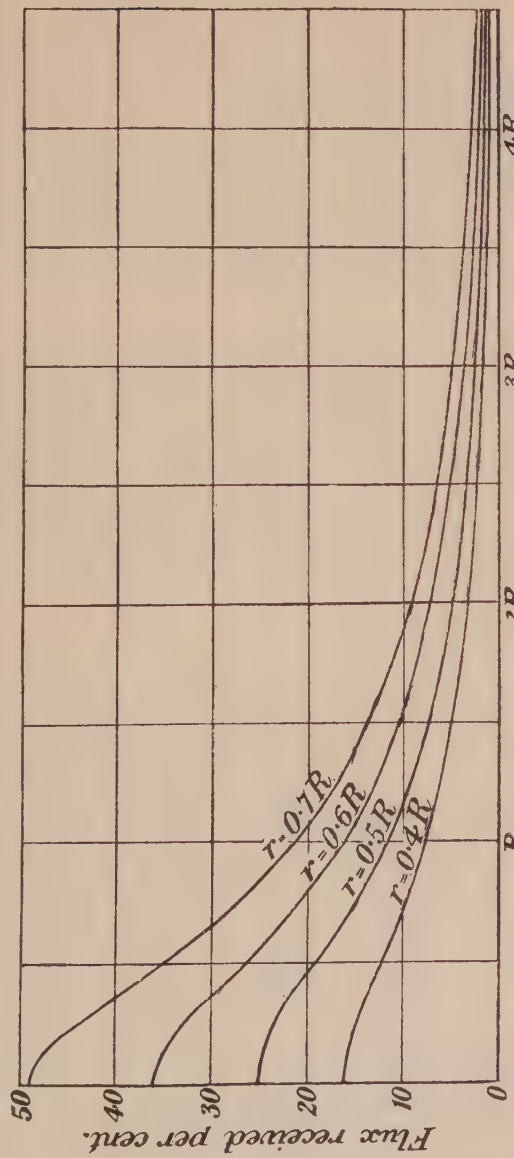

Flux received per cent.
50
40
30
20
10
0
r=0·7R
r=0·6R
r=0·5R
r=0·4R
R
2R
3R
4R
Distance between discs

FIG. 7.

$1{\cdot}6_3$ per cent. for an arc length D and $4{\cdot}4_5$ per cent. for an arc length $D/2$.

These results show that for most practical purposes it is sufficient to assume that the negative obscures as if it were a disc of the same diameter as its end.

In a second part of the Paper will be given a formula for the flux reflected back to a radiating disc by a diffusing parallel and coaxial disc of known coefficient of reflection. A treatment of the problem of the flux received from a radiating disc by a disc which is not parallel with it will also be given.

ABSTRACT.

An expression is obtained for the amount of flux received from a perfectly diffusing circular luminous disc (*i.e.*, one radiating according to the cosine law) by a second parallel and coaxial disc. This is obtained from Sumpner's theory of the whitened globe, and also from first principles. The following applications of the theory are made: (I.) It is shown that the surface traced out by the edges of coaxial discs which receive equal amounts of flux from a radiating disc is an hyperboloid of revolution about the common axis of the discs. (II.) The amount of flux received from a radiating disc by the walls of a cylinder infinitely long in one direction is found.

DISCUSSION.

Mr. T. SMITH was surprised that the results given by the author were regarded as novel. They were almost all cases of problems which had been discussed before, certainly in other connections, and probably in connection with photometry also. Some of the cases considered were well known in optical guise; for instance, the light received by an aperture from a plane extended source of light. They were, perhaps, most extensively discussed as electrical problems, and reference to such books as Maxwell's "Electricity" and Thomson and Tait's "Natural Philosophy" would be likely to reveal close parallels. An examination of the writings of some of the early optical writers, Hamilton for example, might also be profitable. The detailed proof of some propositions—for instance, the equivalence of a circular disc and a spherical cap with the same boundary—tended to obscure the more general result that the boundary to the surface, and not the surface itself, is the relevant factor. This is really the fundamental proposition in the photometry of surfaces, and it is surprising that though it has been known so long it is so easily overlooked. Mathematically, the result at once follows from the fact that the integral is of a type which may be transformed from a surface integral to a line integral round the boundary of the surface.

The AUTHOR (communicated) in reply to Mr. T. SMITH: I shall be very glad to have the references to the previous work on this subject if Mr. Smith will be so kind as to send them to me. I have been able to find nothing except the work of Hyde and Foote referred to in my Paper, and neither of these authors refers to any previous treatment of the matter, except a Paper by Bassett Jones before the Illuminating Engineering Society of New York, "Trans." 5, p. 281, 1910.

The only analogous problem of which I have been able to find a treatment is that of the attraction of a uniform circular disc for a point on its axis. (Thomson and Tait's "Natural Philosophy," 477, Vol. I.) The expression obtained is not the same in the gravitational problem, however, as in this the attraction depends only on the first power of the cosine of the angle between the normal and the line connecting the points considered, whereas in the illumination case it is the square of the cosine that is involved. This arises from the fact that the interposition of matter between two particles does not affect the force with which they attract each other. Thus, there is nothing in the gravitational problem to correspond with the cosine law in the illumination problem.

IX. *A Comparative Method of Testing Thermionic Valves for Passing No Reverse Current at High Voltages.* By N. W. McLachlan, *D.Sc., Eng., M.I.E.E.* (*From the National Physical Laboratory.*)

Communicated by F. E. Smith, O.B.E., F.R.S.

Received October 23, 1919.

In using two electrode thermionic valves for the determination of the maximum or peak voltage of a high-tension alternating supply, and in the determination of the decrement of a circuit in which the damping is very high, it is essential that the valve should pass no reverse current. In order that the above condition is fulfilled, it is necessary to carry out tests at high voltages. The voltages used by the author for experimental work were generally of the order of 10,000, but tests on the valves were conducted up to 18,000 volts.

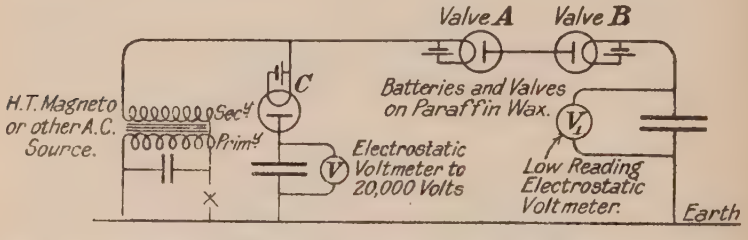


Fig. 1.—Diagrammatic View of Apparatus used for Testing Valves for Passing Reverse Current. (Valve *C* and the Electrostatic Voltmeter reading to 20,000 volts, are used to measure the peak voltage applied to valves *A* and *B*. The negative pole of the battery for valve *C*, should be connected to the source of *A*, *C*. In the diagram the battery connections are shown reversed. When measuring high voltages this is of no importance since the drop in the filament is negligible.)

The simplest method of testing a valve for passing reverse current is to use a high-tension steady source. This can be obtained in the manner indicated by Prof. Fortescue in his recent Paper before the Physical Society.* It often happens, however, that the apparatus needed for this method of obtaining direct current is not available. In this case it is necessary to employ other means.

The apparatus used for testing the valves is shown diagrammatically in Fig. 1. The filament of valve *A* is con-.

* "Proc." Physical Soc., Vol. XXXI., August 15, 1919.

nected to the high-tension side of an alternating-current supply. The anode of *A* is connected to that of *B*. The filament of *B* is connected to one plate of a condenser, which should have good insulation and dielectric properties. The other side of the condenser is put to earth or to the other side of the alternating-current supply. A low-reading electrostatic voltmeter (which should not leak) is connected across the condenser. Both of the batteries for the filaments of *A* and *B*, and also the valves themselves, should be supported on blocks of paraffin wax. In place of a high-tension transformer it was found more expedient to use a polar-inductor magneto which could be run up to 1,500 revs. per min. By cutting out the safety gap it was possible to obtain 20,000 volts. During the operation of the magneto, which would have given 100 sparks per second—*i.e.*, equivalent to a frequency of 50 $\sim$ per second—if used in the normal manner, the peak voltage is alternately positive and negative. On reference to Fig. 1 it will be seen that valve *A* is set to rectify the positive semi-alternation and valve *B* the negative semi-alternation. Thus, if neither of the valves passes reverse current, there will be no reading on the voltmeter *V*. If, however, one valve passes reverse current, whilst the other does not, there will be a reading on the voltmeter, since a current will flow into the condenser and charge it each time the valve passes current, until finally the difference between the peak voltage and the condenser voltage is such that reverse current just ceases to pass. It is impossible to discriminate, however, which of the two valves passes reverse current. This can only be done when either *A* or *B* is known to pass no reverse current at the highest voltage used during the test. Valves can now be obtained, two of which, when tested by the above method, pass no reverse current. The author recently tested two O.R.I. Osram valves up to 18,000 volts by the above method, and obtained no reading on the voltmeter, which latter would readily indicate 5 volts. The filament current of each was 5 amperes, and the duration of the test 20 minutes. Using one of these valves as a standard, it was possible to test other valves when the filament currents were varied. The reverse current depends to a certain extent on the bombardment to which the anode is subjected. If this is severe, the valve will pass reverse current; but under ordinary working conditions there is generally no necessity to resort to excessive bombardment.

Measurement of the Decrement of Highly Damped Oscillations with the Aid of a Thermionic Valve.

In measuring the decrement of highly-damped oscillations—*e.g.*, the oscillations which occur after the interruption of the primary circuit of a magneto—a wavemeter is some-

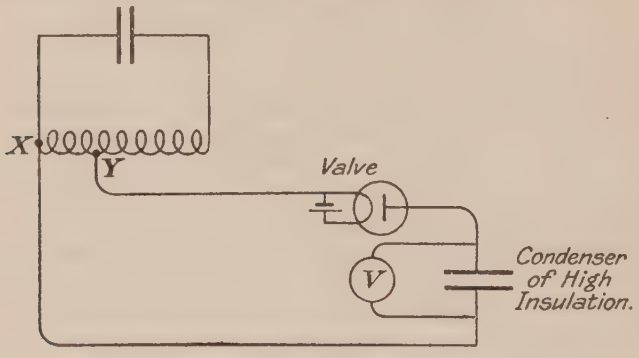


Fig. 2.—Diagram of Apparatus used in Measuring Decrement.

times of little assistance. In cases where it is possible to use a wavemeter, the following provides an additional method. The apparatus is arranged as shown in Fig. 2, where a tapping is taken off the inductance in the oscillation circuit, or a connection made across the condenser, according to the voltage which

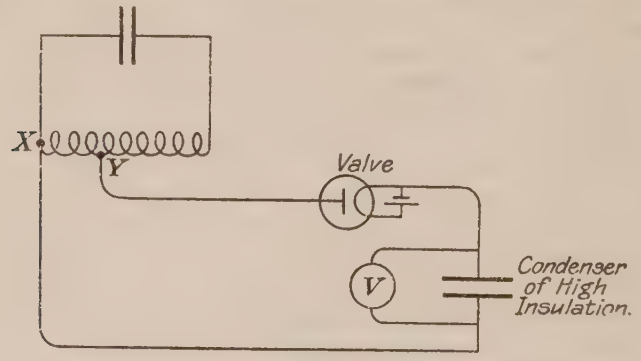


Fig. 3.—Diagram of Apparatus used in Measuring Decrement.

is available. The valve, which is known to pass no reverse current, is set to rectify, say, the negative portions of the oscillations. The condenser will therefore become charged

to a potential equal to the peak voltage which occurs between X and Y in Fig. 2. This potential is proportional to the peak or greatest positive voltage of the train of oscillations. In order to measure the greatest negative voltage, the valve is reversed as shown in Fig. 3. This can be done by means of a switch. The square of the ratio of the voltmeter readings is the decrement of the oscillations per period. It should be remarked that the condenser in parallel with the voltmeter might have some influence on the oscillations in the remainder of the circuit. This, however, is only transient, because once the condenser is fully charged no current flows in the valve circuit, except that due to leakage. The latter can be reduced to a very small quantity by observing the precautions already mentioned, and taking special care that the outside of the battery is dry.

Measurement of the Damping in a Magneto.

The foregoing method of measuring decrement can be applied to the magneto. The oscillations which occur in the primary and secondary circuits after the contacts separate are not damped sine waves, so that the term decrement does not strictly apply. In this case, therefore, the damping will be defined as the ratio of the peak value of the first positive semi-undulation to that of the first negative semi-undulation. It is useful to know this ratio, since it is a rough index of the effect of the iron loss.

There are two values of the damping which can be obtained from the magneto when a current is broken in the primary. One is found with the armature stationary, and fixed in the position at which break would occur in normal running. The other is found when the armature is rotated. Dealing with the case in which the armature is stationary, the circuit of Fig. 4 is utilised. This has been outlined in another communication, and a further description is unnecessary.* It is important, however, to point out that the direction of the current should be the same as that of the induced current during rotation. The reason for observing this precaution can be studied with the aid of hysteresis loops. Before the current is passed through the primary winding, the magnet produces a polarising flux in the armature core, its magnitude being greater at retard than at advance. The current, according to its direc-

* "Proc." Physical Soc., Dec. 1919;

tion, either increases or decreases this flux. The flux change in the armature, and therefore the peak voltage due to cessation of the current, depends on this.

The reading of the voltmeter will be either the first positive or negative peak. It is preferable to obtain the former with the connections of Fig. 4, since there is then less chance of leakage. This can easily be managed by suitable choice of

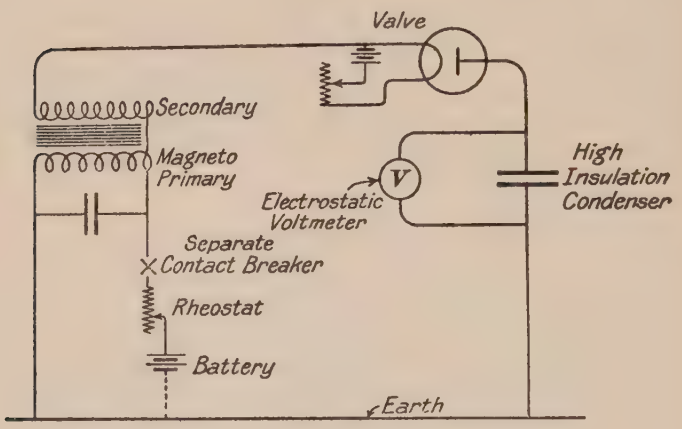


Fig. 4.

the rotor position. The negative peak can be secured in two ways : (*a*) Reversing the valve connections, (*b*) turning the rotor through 180 electrical degrees and reversing the current. In the latter mode of procedure it is essential to assume symmetry for the two positions of the rotor. The determination of the damping when the magneto is in operation can be effected by the same apparatus if the cam is arranged to provide only one break for a rotation of 360 electrical degrees—*i.e.*, alternate breaks are omitted. Under these circumstances, the history of the iron between successive breaks is different from that in normal running. The values of the peak voltages are due to interruption of the current plus the voltage due to rotation, but allowance can be made for the latter.* For strict comparison of this value of the damping with that derived with the armature at rest, the currents should be of equal magnitude.

* "Proc." Physical Soc., Dec. 1919.

ABSTRACT.

A simple method of testing diode valves for passing no reverse current at voltages up to 20,000 is described. The anode of a standard valve, known to pass no reverse current, is connected to that of the valve under test, and the filaments are joined to the terminals of a high-tension alternating voltage supply. A low-reading electrostatic voltmeter, with parallel condenser, is arranged to indicate if the valve under examination passes reverse current.

A description of a method of using a diode valve to measure the decrement of a highly damped oscillation is given. This consists in arranging the valve connections of the circuit so that the first positive peak is obtained. The valve connections are then reversed, and the first negative peak is found. This method is applied to the measurement of the highly damped oscillations which occur after the primary current is broken in a magneto.

X. *On Recording and Reproducing Sounds by Means of Light.* *By* A. O. Rankine, *D.Sc., Professor of Physics in the Imperial College of Science and Technology.*

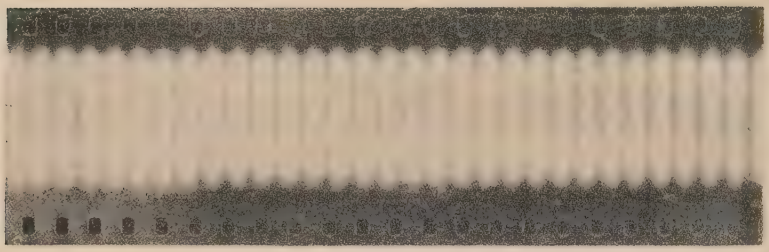
Received November 14, 1919.

(1) *Outline of Experiments.*

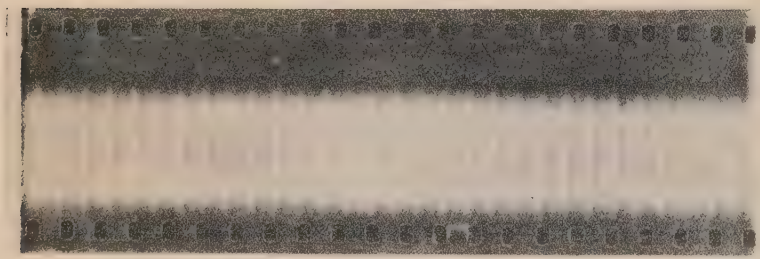
In a recent communication to the Physical Society, I have described a method of transmitting speech by light.* In the discussion following the reading of the Paper it was remarked that the method could be adapted to recording sounds photographically, and afterwards reproducing them. Experiments made since then have shown that this is the case, and the results are interesting in several respects.

It has been customary hitherto to record sounds by transverse vibrations, such as, for example, the trace made by a vibrating spot of light on a moving photographic film. The record thus obtained does not lend itself readily to reproduction; but if, instead, sounds can be recorded photographically by means of changes of *intensity* of a beam of light, reproduction becomes quite easy. This process is not new, having been used in 1900 by Rühmer† in connection with experiments on the electric arc. It was developed by him as a means of testing the conditions under which the greatest variations of light intensity could be brought about by the action of microphonic currents superimposed on the current passing through the arc. He finally succeeded both in recording sounds by this means and in reproducing them; but he points out that the method requires laborious manipulation, owing, mainly, to the difficulty of keeping the arc in the sensitive condition. The photophone transmitter described in my previous Paper avoids this difficulty entirely, and enables photographic records of sounds to be obtained with great ease and precision. This is evident from the fact that the examples shown in Fig. 2 are the results of first attempts, and involved no very careful preparation. Probably they can be improved, but they are already sufficiently good to give accurate reproduction of the corresponding sounds.

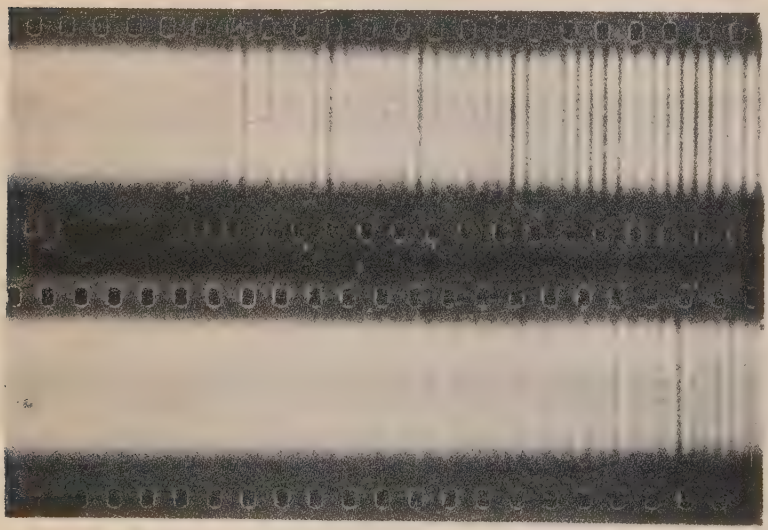
* "Proc." Physical Soc., Vol. XXXI., p. 242.
† Ernst Rühmer, "Wireless Telephony," 1907.



Example I.—Tuning Fork Frequency 512 per sec.



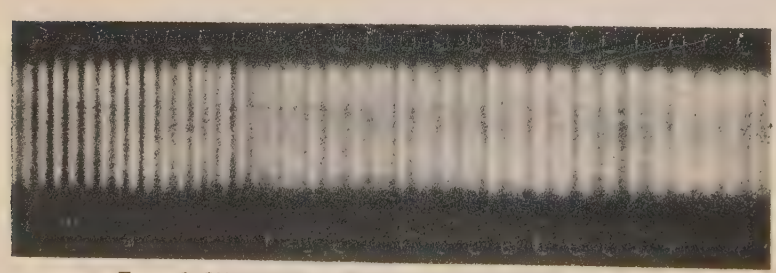
Example II.—Open Organ Pipe. Fundamental Frequency 520 per sec.



(*a*)

(*b*)

Example III (*a*).—Beginning of word "Five."
III (*b*).—Beginning of word "One."



Example IV.—Towards the End of the word "Five."

Fig. 2.

To face p. 79.]

(2) *Production of the Records.*

It is unnecessary to describe again the photophone transmitter. The light from a 500 c.p. Pointolite lamp was passed through the transmitter, and the emergent fluctuating beam, instead of being projected to a distance, was concentrated upon a narrow horizontal slit, S (Fig. 1), by means of the lens L_1. A second lens, L_2, was used to focus an image of the slit upon a band of kinematograph film, which could be moved in a vertical direction. The film was contained in a special camera, actuated by clockwork, which enabled about 2 metres of film to be run at nearly constant speed. In order to obtain as much detail as possible, the image of the slit on the film was made very narrow—between 0·1 mm. and 0·2 mm.—and

FIG. 1.

the film run at considerable speed—about 170 cm. per second. In these circumstances the film was, perhaps, rather underexposed, and improvements could, no doubt, be obtained by using a source of greater intrinsic brilliancy.

Examples of the results obtained are shown in Fig. 2, which represents positive prints taken from portions of the films. Example I. is the record of the vibrations of a tuning fork (frequency 512 per second) bowed and then held near the receiving trumpet of the transmitter. As might have been expected, the fundamental frequency only is indicated. Example II. was produced by an open organ pipe of fundamental frequency, 520 per second. Here the effect of the first overtone (frequency 1,040 per second) is seen superimposed on the fundamental. Examples III.*a* and III.*b* represent respectively the beginnings of the words "five" and "one." Space is not sufficient to show the complete words, each of which, although only a monosyllable, has, on the scale shown, a visible record about 40 cm. long. Example IV. is the record of that part of the word "five" where the "*i*" sound changes to the "*v*" sound. Progression is from left to right, and the change of

character is shown fairly well. Sufficient photographs have been taken to show that in different records of the same word the general features are repeated, although the identity of detail is not, perhaps, as complete as might have been expected. It appears probable that even the same person, speaking the same word several times, does not actually repeat the vibrations identically. At any rate, it is totally unnecessary for him to do so, for, as will be seen later, speech communication requires only the existence of the principle features of the vibrations.

(3) *Reproduction of Sounds from the Records.*

In order to reproduce the sounds from the films, all that is necessary is to focus the light from a narrow source upon the film and allow the light which penetrates the film to fall upon a selenium cell connected with a battery and telephone receiver. A convenient arrangement is shown in Fig. 3, where the light from the arc illuminates the horizontal slit S, and the lens L

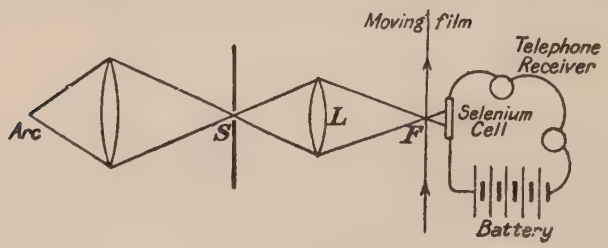


FIG. 3.

produces an image of the slit on the film at F. The light penetrating the film fluctuates when the latter is moved rapidly, and sounds are heard in the telephone receiver. The reproduction thus obtained is good, and there is a quite remarkable amount of latitude in adjustment without noticeable deterioration of articulation. In the first place, it may be noticed that there is no need to use in reproduction a positive of the original negative film ; the negative itself serves quite well. This means that the phase of the vibrations may be reversed throughout without any effect on the sounds heard. Secondly, it is apparently quite unnecessary to take any special care in the development of the film with a view to securing that the opacity is proportional to the intensity of the incident light. It is sufficient that the main frequency charac-

teristics should be represented by alternations of opacity. Further, it is not essential that the speed of the film during reproduction should be precisely the same as that during recording, in so far as the articulation of a word is concerned. The general pitch, of course, changes with speed; but it is possible to recognise the same word even if its record is run at a wide range of speeds. But the most remarkable fact of all is the small effect produced by alterations of width of the illuminating slit. The width of the slit image on the film during recording was less than 0·2 mm., yet in reproduction one can increase its width to considerably over 1 mm. without any marked effect on articulation. This means that the ear can be very easily deceived, and that only a rough approximation to the original vibrations is necessary in the reproduction of sounds required in ordinary listening. The practical effect is that there is no need for the film to be run at so great a speed as that used in these experiments. Probably a speed of 40 cm. per second would be quite sufficient with a slit image 0·2 mm. wide both in recording and reproduction. From the point of view of the visual examination of the records, higher speeds are, of course, preferable.

(4) *Significance of the Records.*

An interesting feature of the records is that they provide pictures of sound waves much more exact than is possible by representing them in the usual way as transverse vibrations. They give, in fact, a fair representation of the condition of *longitudinal* displacements which travel through the air. The changes of photographic density on the film record correspond to the changes of density in the air, and the record of any sound may thus be regarded as an instantaneous picture of the succession of compressions and rarefactions in the associated sound wave.

Different words have records which differ greatly in appearance. By increasing further the speed of the recording film in relation to the width of the slit, it is probable that these differences can be still further accentuated, so as to show clearly the differences between such sounds as, for example, "th" and "z." In this respect they may be useful to students of phonetics. It might even be possible for persons to overcome the difficulty of saying "th" by learning to create the pressure changes indicated on the "th" record.

In conclusion, I wish to express my best thanks to Dr. A. B. Wood for the loan of the camera used in these experiments, and to Mr. F. C. Toy for kindly assisting me in making the records.

ABSTRACT.

The light from the photophone transmitter described by the author in a previous communication (Vol. XXXI., p. 242) is concentrated on a narrow slit, an image of which is produced by means of an auxiliary lens on a strip of cinematograph film, the slit image being transverse to the film. The variation in intensity of the light when sound waves are received by the instrument are recorded as variations in the density of the film after development. For reproduction of the sounds, light from an illuminated slit is focussed on the film, behind which a selenium cell, connected to a telephone circuit, is placed. As the film moves, the intensity of the light reaching the cell varies in accordance with the density of the film, and the corresponding sound is heard in the telephone.

DISCUSSION.

Prof. BRAGG asked if the records contained any clue to the solution of the question how many vibrations were required to give the sensation of pitch. He thought students of phonetics would welcome the apparatus.

Mr. T. SMITH pointed out that no advantage would accrue from the use of a cylindrical lens in the reproducing apparatus, unless the form of the selenium cell rendered it desirable to spread the light over a longer strip than could be obtained with a spherical lens.

Mr. W. C. S. PHILLIPS asked if the experiments would throw any light on the question of resonance in the mouth. The fact that some people speak much more easily than others is generally attributed to the better production of sound. It is sometimes found that, of two voices, that which is loudest and clearest when heard close at hand may not carry nearly so well to a distance. Possibly records of this kind might throw some light on these questions.

Mr. J. GUILD said he hoped the author would continue his experiments until he produced a proper gramophone. Modern gramophones had improved enormously in quality of tone and accuracy of reproduction; but the way in which the time of musical items was juggled with in order to fit them into the record was very annoying. With film records there would be no necessity to spoil pieces in this way.

Dr. D. OWEN raised the question of the accuracy of reproduction. He did not agree with the statement that the ear was easily deceived. In some things—speech for example—we are easily pleased, because we unconsciously attempt to make the best of it; but in music we are much more critical. He thought there should be more accurate reproduction by the author's instrument than by the purely mechanical gramophone; but there would, nevertheless, be distortion of the wave form due to the want of proportionality between the intensity of the sound and the density of the photographic image. Had the author tried reproducing, for example, the tones of a violin? From the scientific point of view, the method was novel, but he thought the records might not be easy to interpret correctly. There was nothing, for instance, to correspond to a change of phase. Again it was stated that the brightness of the light focussed on the film was proportional to the excess of pressure in the wave, and that, therefore, the blackening of the film gave approximately a picture of the rarefactions and

condensations. The light was, however, proportional to the displacement in the wave front, and not to the pressure excess.

Dr. VINCENT thought the instrument would be of value in solving many acoustical problems. One of these was the question of the formation of vowel sounds. The essential points differentiating between various theories of vowel formation could be sifted out from these records by running them at different rates. The difficulty with the older mechanical reproducers was that variation of the speed, except to a very limited extent, introduced mechanical troubles, such as chattering.

Mr. F. E. SMITH said they must not forget the valuable work done in the examination of sounds by the oscillograph. We had also to remember that the telephone came between the selenium cell and the ear, and was an additional cause of distortion.

Prof. RANKINE, in reply, said he had no information on the question asked by Prof. Bragg. A gramophone on the lines of his instrument would be an expensive luxury owing to the cost of the film. With regard to Dr. Owen's points, the records do show change of phase, as the instrument is arranged so that zero displacement corresponds to half intensity in the transmitted light; a displacement in one direction increased the brightness, and a reverse displacement diminished it. As to the meaning of the records, he didn't think the displacement of the diaphragm of the receiver would be that which the air would have had in its absence. The displacement of the diaphragm was more likely to correspond to the pressure in the wave front.

As regards the oscillograph, the difficulty is that for most sounds it is very insensitive, and the addition of an amplifier may produce distortion. In his own instrument there were, of course, several causes of distortion—the receiving diaphragm, the selenium cell and the telephone, in addition to the photographic film, as pointed out by Dr. Owen.

XI. *On some Experiments in which Two Neighbouring maintained Oscillatory Circuits affect a Resonating Circuit. By* J. H. VINCENT, *M.A., D.Sc.*

RECEIVED DECEMBER 29, 1919.

The Ideally Simplified Problem.

IF two valve maintained circuits (Bench 1 and Bench 2, Fig. 1) are so far apart as to have no influence upon each other and one of them (Bench 2) is capable of having its frequency adjusted as desired, then the combined effect on a

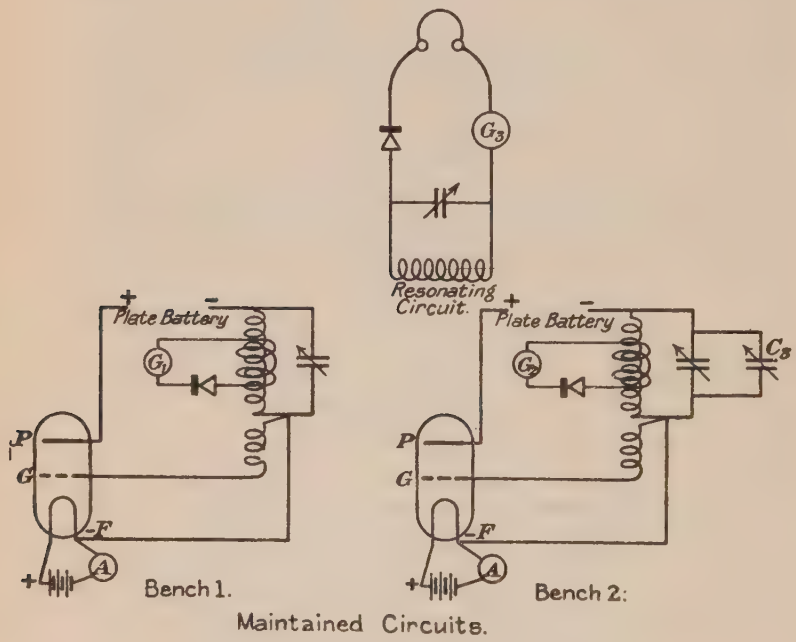


FIG. 1.

resonating circuit such as shown in Fig. 1 when this is assumed to be so distant from each of the maintained circuits as to eliminate any coupling is merely the sum of the effects of the maintained circuits taken separately.

Thus when the Bench 2 circuit is tuned so as to be in absolute unison with the Bench 1 circuit the E.M.F.s and the currents in the resonating circuit will be the sums of the E.M.F.s and the currents due separately to the maintained circuits.

In particular the resultant current in the resonating circuit will be a function of the phase difference between the maintained circuits, and on this view this will be a mere matter of chance. If one induced current in the resonator were of the same amplitude but of opposite phase to the other then no resultant current would flow in the resonating circuit; while if the separate induced currents were of the same amplitude and phase then the combined current would be twice the magnitude of either.

The Actual Problem.

In these experiments the two-valve-maintained circuits are near enough to exert an appreciable effect on each other, which effect may be enhanced by a possible amplifying or minifying influence due to valves.

The resonating circuit (Fig. 1) had its condenser shunted with a carborundum crystal in contact with brass in series with a micro-ammeter (G_3) and a telephone. At times a vibrating galvanometer of low natural frequency, kindly lent to me by Mr. Jordan, was inserted in this circuit. The resonating circuit was not sufficiently distant for us to neglect the possible effects of coupling between this circuit and the maintained circuits; in consequence, a new coupling exerted on one maintained circuit by the other through the effect on the resonating circuit, may exist.

Finally, no direct measure of the current in the resonating circuit was made; the readings of the galvanometer G_3 in series with the detector were the subject of the observations so that the properties of the detector are involved in the work.

Apparatus.

The two maintained circuits were set up on two work benches placed a few feet apart as shown diagrammatically in Fig. 1.

There was no method available of measuring the alternating currents in the oscillators directly, but each main oscillating coil was wound with a few turns of insulated wire in series with a micro-ammeter and crystal detector. These micro-ammeters are referred to as G_1 and G_2 respectively.

The axes of the main oscillating coils of these two circuits were parallel and were connected up to the high potential batteries so that the currents through the valves made the

end of Bench 1 coil nearer the resonating circuit have south-seeking polarity and the corresponding end of the Bench 2 coil have north-seeking polarity.

The axis of the coil of the resonating circuit was parallel to the line joining the ends of these two coils and a few feet away; so that if the two maintained circuits were in the same phase the induced E.M.F.s in the resonating circuit would be conspiring together.

The frequencies used in drawing the Figures 2, 3, and 4 were of the order of 100,000 per second, but widely differing frequencies have given similar effects.

Results.

As the frequency of the Bench 2 circuit is lowered by gradually increasing its capacity we pass from a condition in which Bench 2 is sharp on Bench 1 to that in which it is flat. We thus pass through the state of absolute unison. The capacity change per degree of small condenser in the Bench 2 circuit is about one-tenth of a centimetre, the main capacity being about 450cm. Thus a very slow adjustment of frequency is possible.

When the resonating circuit is carefully tuned to the Bench 1 circuit the circumstances are illustrated in Figure 2. When valve on Bench 1 only is alight the deflection of G_3, the galvanometer in the resonating circuit, is given by the line AB. When that on Bench 2 only is operating the deflect on of G_3 is given by the curve CD, in which the ordinates are the deflections and the abscissæ the settings of the small condenser.

When both valves are lit the effects are shown by the curve EF. As the capacity increases the deflection G_3 increases; the pitch of the telephone note falls uniformly with the increase of the Bench 2 capacity as indicated by the line LM. Such lines were drawn from observations with standard forks by R. Koenig. As the point G is approached G_3 shows signs of vibrating. This vibration decreases in frequency until M is reached. The oscillatory current in the resonating circuit is practically zero, the deflection of G_3 is zero and the needle shows no signs of vibration. In the observations any direct-current galvanometer can be used. The description applied particularly to the behaviour of a Paul Uni-pivot instrument giving a deflection of 1 scale division for two micro-amperes. The two maintained circuits are now vibrating in unison and in the opposite phase.

On further increasing the capacity the two circuits are gradually brought into phase, at J this is complete. The change in Fig. 1 from M to J is brought about by an increase

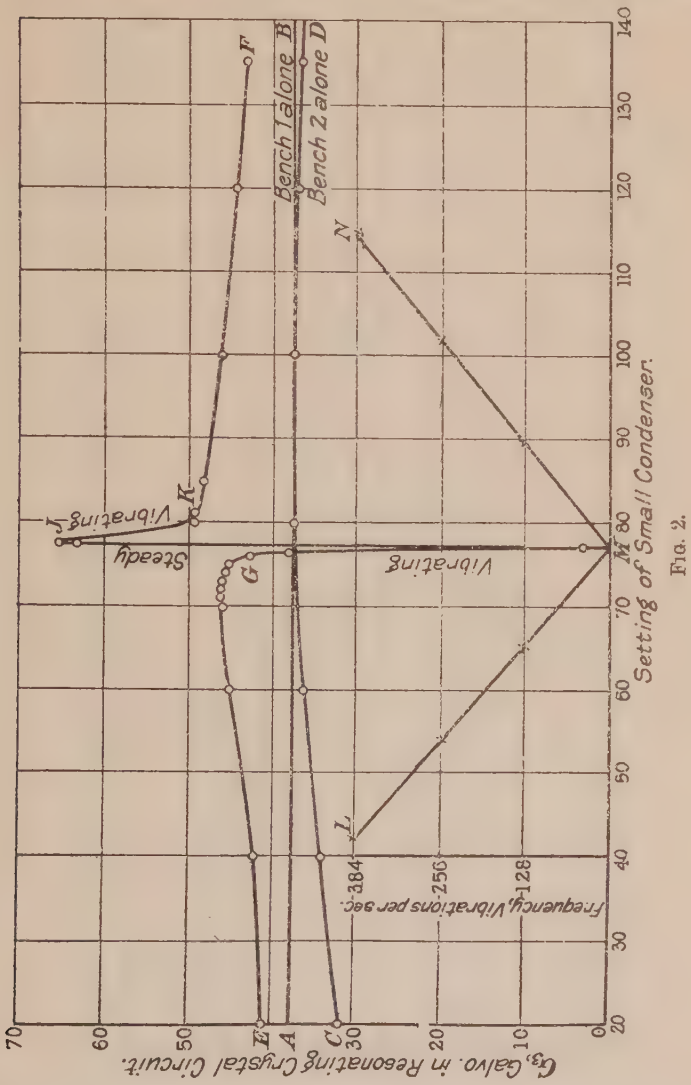


Fig. 2.

in capacity of a twentieth of a centimetre in a total capacity of 450cm. During this change from M to J the needle of G_3

does not vibrate; nor does a very low frequency galvanometer oscillate if included in the circuit.

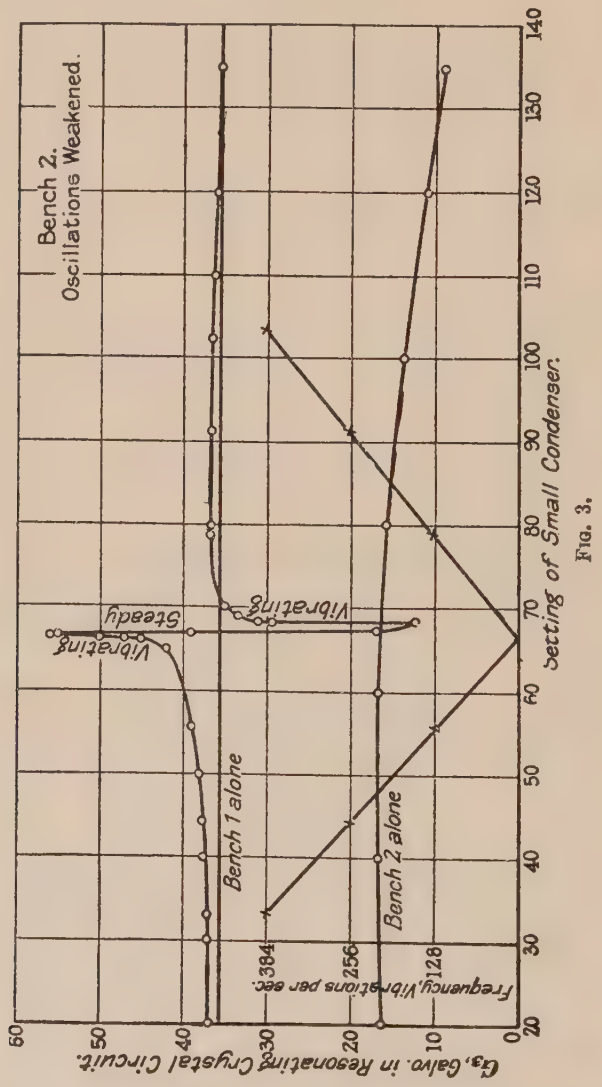


FIG. 3.

When the capacity is made still greater G_3 shows oscillations and the deflection falls

The line NM is again a practically straight line, the dead space from M to the projection of J, during which change in

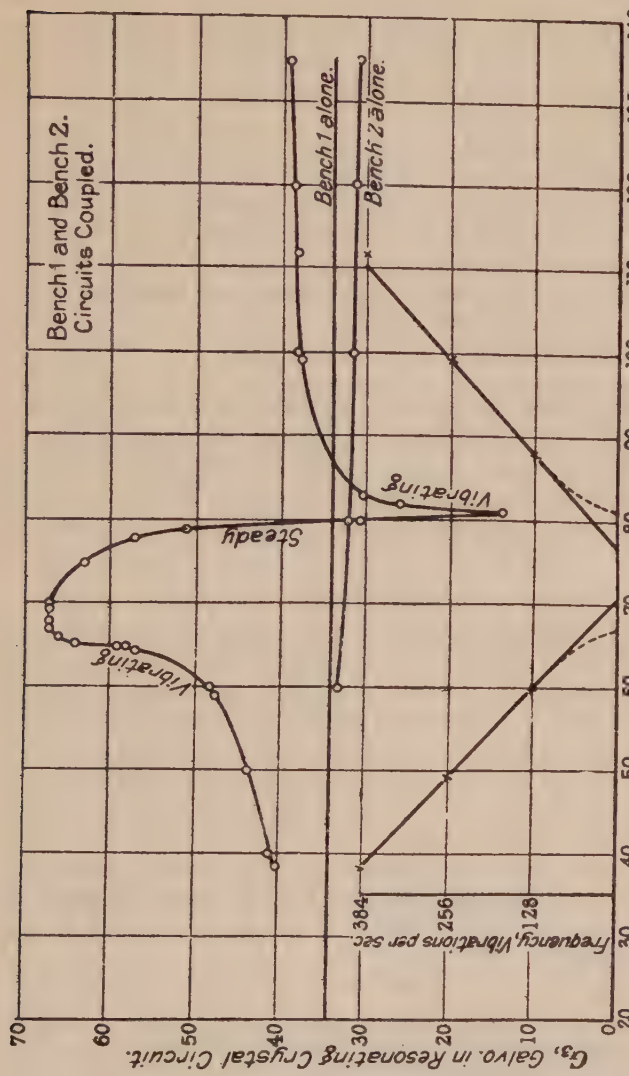


FIG. 4.

capacity does not alter the frequency, being too small to show clearly on records of the tuning fork observations.

The question immediately arises as to what settles whether the minimum or the maximum deflection of G_3 occurs first as the capacity increases.

It was found that when the amplitude of the oscillations in either circuit were sufficiently reduced (as judged by the galvanometers G_1 and G_2) the minimum occurred first or second according as the Bench 1 or Bench 2 circuit was weakened.

When a resistance is put into the Bench 2 circuit in series with the main oscillator coil the minimum occurs at a higher setting of the condenser than for the maximum. (Fig. 3.)

It was also found that accurate adjustment of the resonating circuit was not necessary. Similar results are obtained even when the resonating circuit is purposely mistuned in either direction to a considerable degree.

The curves giving the deflection of G_3 as a function of the setting of the small condenser are very much altered by introducing coupling between the two maintained circuits. In particular the dead space over which the capacity can be adjusted without change in frequency is very much increased by joining the negative ends of the valve filaments to the terminals of an air condenser of 12cm. capacity. (Fig. 4.)

Conclusion.

The experiments described above provide a means of observing small changes of frequency which have hitherto been studied by the method of beats. The observer merely has to note the setting of the condenser when the maximum or minimum deflection on the galvanometer occurs. This method is one requiring little training, and which is not fatiguing to the observer. It has been tried on previously known curves with success.

These experiments were carried out in Dr. Eccles' laboratory at Finsbury Technical College. I have great pleasure in thanking him for the encouraging interest he showed during their progress.

ABSTRACT.

Two valve-maintained oscillating circuits, one of which is provided with an adjustable subsidiary condenser of small capacity, each cause oscillations in a third resonating circuit. The third circuit has its condenser plates connected through a crystal detector and galvanometer. When the maintained circuits are in unison a very small change in the capacity of the subsidiary condenser causes the galvano-

meter needle to move through a large angle. The method provides a means of observing small changes of frequency previously studied by the method of beats.

DISCUSSION.

Dr. Eccles pointed out that Dr. Vincent's addition of the second high-frequency oscillation generator to the ordinary wave-meter method of working had resulted in an extraordinary enhancement of the accuracy of measurement of wave-length. It was very surprising to watch the sudden drop of the pointer of the table galvanometer in the crystal circuit as the second oscillator was brought into exact tune with the first. In this tuning process variations of capacitance of less than one-tenth of an electrostatic unit could be made evident by the table galvanometer in a total capacitance of 250 cm.—equivalent to detecting a change of radius of 1 mm. in a sphere of 25 metres radius. The method was far more accurate than that of the ordinary heterodyne wave-meter, and abolished the tediousness of using telephones. It promised to become a standard method of measuring wave-lengths.

Prof. O. W. Richardson said he was struck by the similarity of the curves to those representing anomalous dispersion in the neighbourhood of an absorption band. The explanation was doubtless similar in the two cases.

Mr. Webb said he had been working with the apparatus, and it was so sensitive that anyone moving even at a considerable distance caused large movements of the indicator. Despite this the method gave constant results for periods extending over several hours.

Prof. Lees asked if it mattered whether the condenser C_3 was in front of or behind the oscillating coil.

Dr. Vincent thought Prof. Richardson's simile was very suggestive. He had not been able in the present Paper to go into the detailed theory of the experiments, but he thought the theory when fully investigated would confirm Prof. Richardson's view. It was necessary to get good results, of course, to use all the tricks of the trade to maintain constant conditions in the circuits. Dr. Eccles and he had discovered a simple expedient for maintaining the frequency of the oscillations constant over long periods. This was to adjust the filament current so as to secure the maximum wave-length for the circuit in which the valve is employed. He could not answer the President's question off-hand.

XII. *Measurement of the Chief Parameters of Triode Valves.* *By* W. H. Eccles.

Received January 5, 1920.

1. When a tube is about to be put into use we require to know one or two commonplace facts concerning it, such as the appropriate filament current and voltage, which are easily found out or can be supplied by the maker. But there are other properties of the tube—such as the voltage ratio under conditions of normal use—which usually have to be specially measured, and which are essential for the formation of an accurate forecast of the performance of the tube in particular applications; for instance, in an amplifier or in a receiving set. A large number of parameters have been suggested for expressing numerically the various properties of triodes, but not all of them are equally important nor are all of them independent—that is to say, some of them can be deduced from others. By careful selection it may in time become possible to convey by quite a small number of parameters practically all the information requisite in practice. We shall, in fact, omit from the present section a number of suggested parameters or "constants," which depend jointly on properties of a tube and of the circuit it happens to be placed in, and we shall confine our attention to parameters belonging purely to the tube. Mixed functions of the tube and its circuits can usually be deduced from the data of the circuits of the true parameters of the tube itself.

2. At any given filament voltage or current the principal parameters of a triode are :—

(1) The co-ordinates of the mid-point of the straight part of the lumped characteristic.

(2) The voltage factor g.

(3) The differential co-efficient di_a/de_a or h_a.

(4) The differential co-efficient di_a/de_g or h_g.

Here i_a represents the anode current, e_a the anode voltage and e_g the grid voltage relative to the filament; the quantity e_a+ge_g is called the lumped voltage e_l and the curve connecting the anode current with the lumped voltage is called the lumped characteristic.

If these parameters are all supposed to relate to the regular parts of the lumped characteristic and not to extreme and

unusual adjustments, the last-named parameter is not independent of the preceding two since $h_g = gh_a$. Other data of importance (but not discussed in this Paper) are :—

(5) The value of the anode voltage which just fails to draw the full saturation current given by higher voltages.

(6) The differential co-efficient di_g/de_a or g_a.

(7) The differential co-efficient di_g/de_g or g_g.

(8) di_a/de_f or h_f and di_g/de_f or g_f.

In addition, data concerning the knees of the characteristic curve are of value in connection with the use of the tube as a detector.

3. All these parameters belong wholly to the tube,—that is to say, they are not affected in value by the presence of the apparatus with which the tube is used and are, so far as is investigated, independent of the frequency. From a knowledge of these magnitudes the main aspects of the behaviour of the triode when connected to any kind of apparatus can be calculated. All of them can be deduced from the characteristic curves of a tube, but as the drawing of a number of complete curves is laborious we proceed to indicate various methods of determining the most important parameters direct.

4. The quantities g, h_a and h_g as well as some of the others are either mere ratios or are of the nature of conductances. Their measurement can, therefore, be reduced to the comparison of resistances, which can by the aid of resistance boxes be accomplished conveniently and accurately. But several of the measurements, notably those of parameters defined by differential co-efficients, are concerned with small changes in relatively large currents or voltages, and it is evident that if all of a large current is passed through a galvanometer the sensitiveness for small changes must be low. We therefore adapt some of the general methods of the physical laboratory to our purpose, methods such as the various resistance bridges, the compensation method, or methods using the differential galvanometer ; in all of which the galvanometer can be maintained in its most sensitive adjustment and be kept near its zero, although large currents are running in the things being measured. Only the compensation methods as developed by the writer are described in this Paper.

Remarks on Direct-Current and Alternating-Current Methods.

5. Direct-current methods have certain advantages over methods using rapidly alternating currents and a telephone receiver, though they are not so quick and convenient. An alternating current gives rise to alternating electric and magnetic forces round the various portions of the circuit it flows in, and these forces excite alternating E.M.F.s in neighbouring conductors and also in the different parts of its own circuit; in other words, the accidental electric coupling and magnetic coupling between portions of the same and other circuits produce E.M.F.s and these add subtly to the E.M.F.s applied for the purpose of the measurement. The effects are greater the higher the frequency of the alternations, and are usually too easily evident at ordinary acoustic frequencies. If these unwanted E.M.F.s happen to be in phase with the applied E.M.F.s it is possible to obtain silence in the telephone, but the balance adjustment so obtained will usually be farther wrong the stronger the induced stray effects. If, on the other hand, the stray E.M.F.s are not in phase with the applied E.M.F.s it is impossible to obtain a perfect balance.

In order to minimise these alternating-current disturbances it is well to run as much as possible of the connecting wiring through metal pipes, or to wind the insulated wires with lead or tin foil, and to connect all this metal covering to earth. It is necessary also to place coils in such relative positions that they have the least possible coupling with other coils, and to place condensers and other conductors of large surface well away from each other.

Co-ordinates of the Mid-Point.

6. The first important parameters are the co-ordinates of the mid-point of the straight part of the lumped characteristic. The most obvious and direct method for determining the lumped voltage of the corresponding current at the mid-point of the characteristic curve is to apply known grid voltage and anode voltage, to increase the latter until the saturation current is reached, to divide the magnitude of this by two, and then reduce either grid or anode voltage till the current becomes half of the saturation value. But the last step demands the use of calibrated sources of voltage, and as these are not always at hand, the following less direct method is recommended.

The connections are shown in Fig. 1. The galvanometer I' ought to be of low resistance compared with that offered to

the current by the internal path between anode and cathode. The filament E.M.F. or current must first be set at the desired stationary value by aid of the voltmeter V or otherwise, and the variable resistance R made zero. Then increase the anode voltage E by steps till the current as registered by the galvanometer I ceases to increase. Observe these values of

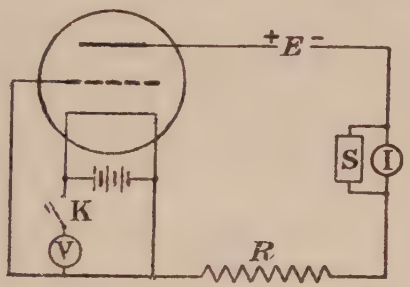


FIG. 1.

anode voltage and current and then add resistance R to the anode circuit until the galvanometer reading is reduced to one-half the saturation value or i_1. Then the required co-ordinates are i_1 and $e_1=E-Ri_1$. It should be noticed that this simple experiment gives information of great utility in connection with trials for amplifiers, for the voltage e_1 is that lumped voltage which must be applied to the tube in order to bring the steepest part of the characteristic into use ; and if the voltage on the grid is zero, then e_1 is the voltage which must be applied to the anode. As an example, in a certain tube with a filament voltage of 5·2V a voltage of 300 secured a saturation current of 10 mA. By adding $R=2800\,\Omega$ in series the current was reduced to 5 mA, the grid being connected all the time to the negative side of the filament. Therefore, $e_1=300-28\times5=160$ V. The result is, it should be noticed, a lumped voltage ; it may be made up by any anode voltage and grid voltage that satisfy the equation

$$e_a+ge_g=160.$$

For example, if $g=10$,

we may have

e_a	e_g
100	6
130	3
160	0
190	−3
220	−6

Any of these settings will give practically the steepest part of the characteristic.

Compensation Method for Determination of h_a.

7. The method to be described is applicable at any setting of anode and grid voltages. The connections are explained by Fig. 2.

The anode battery is indicated by E, the grid potential divider by PD. A sensitive galvanometer with its shunt at IS. The compensation circuit includes the galvanometer, the battery e of smaller voltage than E, and the adjustable resistances R, R_1. The grid is permanently connected to the

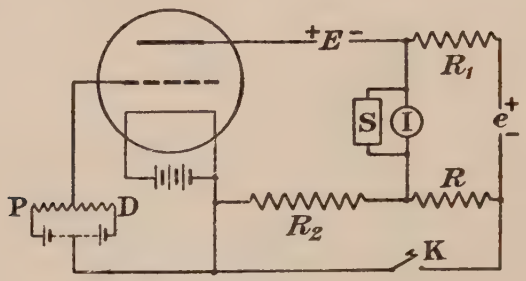


Fig. 2.

filament throughout the experiment and the grid voltage is, therefore, invariable. After the values of the anode, grid and filament voltages have been settled, the procedure is as follows: First, the galvanometer being shunted and the key K being closed, the resistance R_2 is given any value, R a small value (between 10 and 100 ohms in the case of a receiving tube) and R_1 a larger value (about 1,000 ohms), and the latter adjusted until the deflection of the galvanometer is zero. Then the key K is opened and R adjusted until the deflection is again zero. The shunt is now weakened, the key closed, and R_1 more accurately adjusted than before to obtain zero deflection, and then the key is opened and R improved in adjustment. The process is repeated to any required degree of accuracy.

Zero deflection of the galvanometer implies that the P.D. between its terminals is zero. Therefore, when the key is open, the voltage applied in the anode circuit is $E-R_2 i_a$; similarly, when the key is closed the voltage is E. Here i_a represents the anode current when the key is open, and is equal

to the current in the compensation circuit. Let e represent the voltage of the battery in this circuit, then

$$i_a = \frac{e}{R_1 + R}.$$

The current when the key is closed is e/R_1. Hence, on closing the key the anode voltage increases by the amount $R_2 i_a$, and the anode current increases by

$$\frac{eR}{R_1(R_1+R)} \text{ or } \frac{Ri_a}{R_1}.$$

Since the grid voltage is constant throughout the experiment, the ratio of the increase of anode current to the increase of anode voltage gives

$$h_a = \frac{R}{R_1 R_2}.$$

A telephone and interrupter may be substituted for the galvanometer in the above method, the procedure being precisely as just described. See §5 regarding experimental precautions.

The following measurements were made by students at the City and Guilds Technical College, using direct current. They found that when R_2 is taken of small magnitude R must be finely subdivided in order to obtain accuracy. In the case below with $R_2 = 10$ ohms the subdivision of the resistance box used to supply R was not fine enough.

R_2.	R_1.	R.	h_a.
10	930·7	0·7	$7·5 \times 10^{-5}$
200	928·6	13·0	7·00
800	927·5	52·0	6·88
1,000	926·0	65·5	7·1
1,045	924·0	67·0	6·9
1,200	927·2	78·0	7·03
2,000	927·9	130·1	7·06
5,000	928·9	323·5	6·95

Average value of $h_a = 7 \times 10^{-5}$
$E = 174$ volts.
$e = 8$ volts.

A measurement made by Mr. R. H. Rinaldi on another triode gave

$$R_2 = 2050, \qquad R_1 = 903, \qquad R = 43,$$

all in ohms, yielding $h_a = 2·33 \times 10^{-5}$mho.

Compensation Method for Determination of h_g.

8. The method to be described is applicable to any setting of the grid and anode voltages, and is explained by Fig. 3. The grid is connected to the filament direct when the key K is depressed and through R_3 when the key is open. After the values of the grid, anode and filament voltages have been settled the measurement is performed as follows :—

The galvanometer being shunted and K open, the resistance R is given a small value and R_1 a larger value, which is adjusted till the deflection of the galvanometer is zero. The

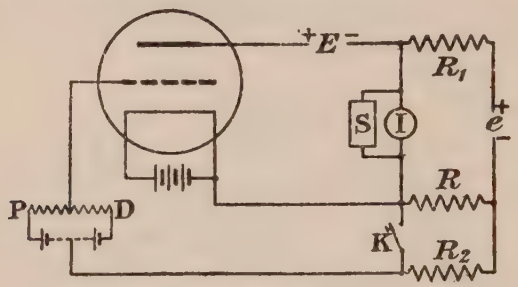


Fig. 3.

key K is now depressed and R_3 adjusted by trial till the deflection of the galvanometer is again zero. The shunt is then weakened, the key opened and R_1 adjusted more accurately than before. The key is depressed and R_3 again adjusted. The process is repeated to any required degree of accuracy.

When the key is down the current in the compensation circuit and therefore that entering the anode is determined by R_1 in series with R and R_3 in parallel ; when the key is up this current is determined by R and R_1 in series. In the former case the current being equal to e divided by the resistance, is

$$\frac{e(R_3+R)}{R_1R_3+R_1R+R_3R},$$

and in the latter case is

$$\frac{e}{R_1+R}.$$

Hence, the increase of current when K is depressed, being the difference of the last two expressions, is

$$\frac{R^2e}{(R_1+R)(R_1R_3+R_1R+R_3R)}.$$

Again, when the key is down the voltage on the grid is that applied by PD; when K is up the grid voltage becomes smaller by the amount of the potential drop along R, namely,

$$\frac{Re}{R_1+R}.$$

Moreover, the anode voltage is the same whether the key is up or down, since zero deflection of the galvanometer implies that the P.D. between its terminals is zero, and therefore that E is the only voltage in the anode circuit. Hence, when the key goes from the open to the closed position the anode current and the grid voltage both rise, while the anode voltage remains constant, and therefore the ratio di_a/de_g is

$$h_g=\frac{R}{R_1R_3+R_1R+R_3R}$$
$$=\frac{1}{R_1+R_3+(R_1R_3/R)}.$$

A telephone and interrupter may be substituted for the galvanometer in the above method, the procedure being precisely as just described. See §5 regarding experimental precautions.

A measurement made by Mr. R. H. Rinaldi, using the direct-current method, gave

$$R_3=90, \qquad R_1=907, \qquad R=43\text{ohms}$$

and $$h_g=3{\cdot}46\times10^{-4}\text{mho}.$$

Compensation Method for the Determination of g.

9. In regular parts of the characteristics the voltage factor g is equal to the ratio of h_g to h_a, and therefore need not be determined separately if h_a and h_g have already been measured. In any case g may be determined direct by the method sketched in Fig. 4.

The apparatus is the same as in the preceding paragraphs, except for the switch.

First, the compensation circuit is adjusted by variations of R_1, the switch being in the position marked 1; then the switch is moved over and R_2 is adjusted till the deflection is again zero.

When the switch is in the position 2 the anode voltage is $E-R_2i_a$, and the grid voltage is that applied by the potential

divider PD. When the switch is moved to position 1 and zero deflection is obtained by varying R_2, the anode current is the same as before because made equal to the compensation current, which is unaltered. Moreover in position 1 the anode voltage is E and the grid voltage is Ri_a below that applied by PD. Thus the fall of the grid voltage Ri_a neutralises the rise $R_2 i_a$ of the anode voltage and therefore

$$gRi_a = R_2 i_a$$

or

$$g = R_2/R.$$

When the grid current is extremely great, relatively speaking, an error arises in the above measurement because current is

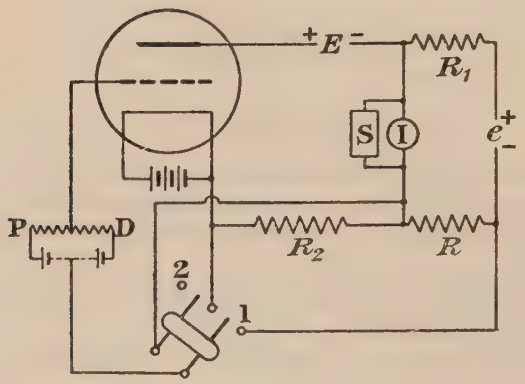


Fig. 4.

drawn from the compensation battery to the grid. This is, however, a rare event.

Measurements of g by the direct-current method give pairs of values for R and R_2, such as 50 and 900, 150 and 2,500, 220 and 3,960, all yielding 18 as the value of the voltage factor for the small receiving triode under measurement.

Combined Apparatus for Determination of h_a, h_g and g.

10. The three methods of measurement just described may be carried out by the aid of the single piece of apparatus sketched in Fig. 5, wherein the letters have the same meaning as in Figs. 2 and 3. The special feature is the six-point switch with which is combined the key K of Figs. 2 and 3. Mercury pools are used in order to ensure good contacts.

Referring to the circuit diagram, when the switch is in the left-hand position marked a the connections are as required for determining h_a, as described in §7, balance of the galvanometer being sought for in both the up and down positions of the chopper key. When the switch is in the right-hand position marked g, the connections are those of Fig. 3, and h_g may

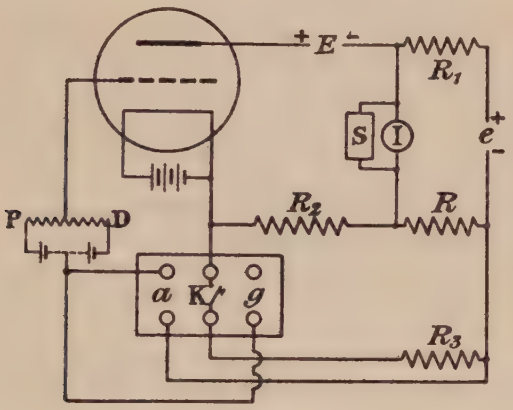


Fig. 5.

be determined by balancing the galvanometer for both the up and down positions of the chopper key. But when the magnitude of R_2 is so chosen that zero deflection is obtained when the switch is in either position with the chopper key up all the time, then the value of g is given by the ratio of R_2 to R, as explained in §9. In cases where the grid current is large, it is advisable to make R_3 zero during the determination of g.

Appendix.

The following Papers deal with portions of the theory and describe methods of measurement bearing upon the points raised in the present Paper :—

T. Langmuir. "Pure Electron Discharge," "Proc." Inst. Radio Engineers, page 261, Vol. III.

M. Latour. "Discussion of the Audion," pp. 280-282, "The Electrician," Dec. 1, 1916.

G. Vallauri. "Comparative Experiments on Audions," "Elettrotecnica," pp. 335-342, June 23 ; and "Elettrotecnica," pp. 350-355, July 5, 1917.

J. M. Miller. "A Dynamic Method for Determining the Characteristics of Three-Electrode Vacuum Tubes," "Proc." Inst. Radio Engineers, p. 141, June, 1918.

E. V. Appleton. "A Thermionic Valve Slopemeter," "Wireless World," p. 458, Nov. 1918.

John R. Carson. "A Theoretical Study of the Three-Element Vacuum Tube," p. 187, "Proc." Inst. Radio Engineers, April, 1919.

Stuart Ballantine. "The Operational Characteristics of Thermionic Amplifiers," p. 129, "Proc." Inst. Radio Engineers, April, 1919.

H. J. Van der Bijl. "Theory and Operating Characteristics of the Thermionic Amplifier," p. 97, "Proc." Inst. Radio Engineers, April, 1919.

H. W. Nichols. "The Audion as a Circuit Element," "Phys. Rev." 13, pp. 404-414, June, 1919.

W. H. Eccles. "An Investigation of the Internal Action of a Triode Valve," "Radio Rev." Oct., Nov., Dec., 1919.

——. "Vector Diagrams of some Oscillatory Circuits used with Thermionic Tubes," "Proc." Phys. Soc. April 15, 1919.

ABSTRACT.

At any given filament voltage or current the principal parameters of a triode are:—

1. The co-ordinates of the mid-point of the straight part of the lumped characteristic.
2. The voltage factor g.
3. The differential coefficient di_a/de_a or h_a.
4. The differential coefficient di_a/de_g or h_g.

Methods of determining these quantities are described.

DISCUSSION.

Prof. Fortescue said the author had described some very nice methods for getting certain parameters of a valve; but he felt they were somewhat academic. There were two aspects in all these problems, namely, the practical and the instructional, and he thought Dr. Eccles had allowed the latter to predominate in devising the methods. For practical purposes one would frequently want to test the complete characteristic of a valve, and he would, on the whole, prefer the old arrangements. He did not think the author had emphasised sufficiently the importance of maintaining the filament current at a pre-determined value. The methods which he mentioned would give great accuracy, but they would be sensitive to very small variations of the filament current.

Prof. G. W. O. Howe said that the suggestion of a single "lumped" characteristic was attractive, yet in practical work it was very desirable to have the various characteristics for different grid voltages. He had been rather mystified by the author's opening remarks concerning Ohm's law.

To say that a valve obeyed Ohm's law when all the "constants" concerned follow complicted laws for different voltages and currents appeared to be stretching the meaning of Ohm's law to an inadmissible extent.

Prof. O. W. Richardson emphasised the remarks of the previous speaker regarding Ohm's law. He could see no reason for saying that Ohm's law applied where the resistance varied with the current and voltage.

Mr. F. E. Smith thought the methods given by Dr. Eccles would be exceedingly valuable where large numbers of valves had to be tested. He would like to emphasise Prof. Fortescue's caution about the constancy of the filament currents.

Prof. A. O. Rankine said: There is a point in connection with triodes concerning which I wish to ask the advice of the author. It refers to the use of triodes in that extreme case of low frequency, namely, when the voltage to be amplified is constant. Suppose that this E.M.F. is associated with a circuit which can be made of very low resistance, such, for example, a thermo-electric E.M.F. In that case, in the absence of means of amplification, the most sensitive arrangement is that in which the resistance of the measuring galvanometer is as low as may be consistent with galvanometric efficiency. The question is whether, in these circumstances, amplification of voltage by one or more triodes will be actually advantageous. If the limitation which I suspect does exist, it is important that the fact should be known; if it does not, the knowledge is, perhaps, of even greater importance, in view of the wide additional field which would be opened for the application of triodes. But, in either case, an authoritative opinion is required. The view I take of the question, subject to correction, is as follows: The output voltage of a triode is necessarily in a circuit of high resistance, for the latter includes the space between filament and plate, and it is therefore measured most efficiently by a detector of high resistance or impedance. But when the input voltage *need* only be in a circuit of *low* resistance, the fact that the E.M.F. is amplified by the triode may not be sufficient to compensate for the original loss of power involved by connecting the input voltage to the filament and grid, between which the resistance is large. A numerical example may be used to illustrate this point. Suppose that the E.M.F. to be amplified is E, and that it is associated with a resistance of 5 ohms. The most efficient galvanometer for direct measurement would have 5 ohms resistance. Thus, the current would be $E/10$ and the *power* operating on the galvanometer $\frac{E}{10} \cdot \frac{E}{2} = \frac{E^2}{20}$. Now, suppose the triode gives a voltage amplification of 10, and that the resistance between filament and plate is 50,000 ohms. In this case 50,000 ohms is the best resistance for the galvanometer, the current is $10E \times 10^{-5}$, and the power available $10^{-4} \cdot E \times 5E = \frac{E^2}{2{,}000}$, or only 1 per cent. of that obtained without the triode. Thus, several more triodes in cascade would probably be required to make up the leeway lost in the first, involving considerable increase of apparatus and multiplication of valve disturbances. The objection does not, of course, apply to the amplification of alternating and intermittent voltages, even when they occur in low resistance circuits, for in such cases the E.M.F. can be transformed up, without considerable less of energy, before being introduced into the triode.

Dr. Eccles, in reply, said that as regards the objections raised to mentioning Ohm's law in connection with the complicated actions in a triode vacuum tube, he thought it admissible to consider that Ohm's law applied instantaneously at any point of the curve connecting the space charge current with the E.M.F. applied between anode and cathode because the value of the current is obtained by dividing the sum of the E.M.F.s (including the back E.M.F. due to space charge) by the resistances (including the differential resistance). Both back E.M.F. and differential resistance are

constant during an infinitesimal change of current and E.M.F., because they belong to the tangent line of the characteristic curve. In reply to Prof. Rankine, leaving aside rapidly varying currents and voltage, the use of a single triode valve for amplifying slowly varying currents or voltages is, as a rule, advantageous only when the supply of energy is strictly limited, and is in the form of a small quantity of electricity at relatively high potential or as a small current in a very high resistance. In such cases if the energy can be conveyed to the grid of the triode and spent in raising its potential. The release of energy in the anode circuit is very much greater and is in convenient form. In the case of the low-resistance thermo-junction problem suggested by Prof. Rankine the junction is a heat engine supposed provided with a source of heat capable of supplying energy for any length of time, and at a rate very largely in excess of what can be consumed in exciting the grid of the tube; therefore, the use of the triode can add neither to the convenience nor to the sensitiveness of the direct galvanometer method. Of course, if on any occasion a very high resistance galvanometer were the only one available it would be better to use a triode, or a sufficient number of triodes in parallel, with anode resistance approximately equal to that of the galvanometer.

XIII. *A Method of Measuring the Amplification of a Radio-frequency Amplifier.* *By* F. W. JORDAN, *B.Sc.*

RECEIVED NOVEMBER 29, 1919.

THE particular amplifier examined by this method was the French Radio-frequency Amplifier, Type L. 1. This instrument was designed for the reception of damped or variable radio-frequency waves such as occur in wireless signalling and telephony. This method of measuring the amplification was devised to suit this kind of reception. Continuous waves can also be received by combining a heterodyne with this amplifier.

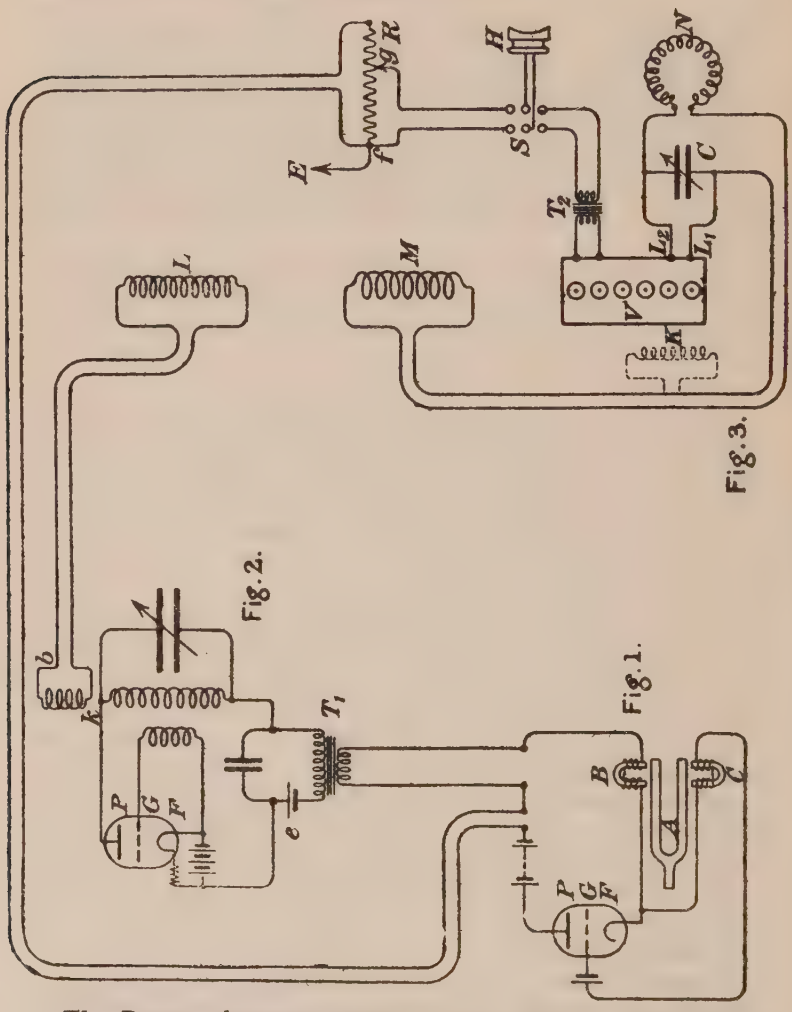
The amplifier consists of six valves—three for the amplification of the radio-frequency, a fourth for the rectification of the latter and its conversion to audio-frequency, and the fifth and sixth for the amplification of the audio-frequency oscillations.

The radio-valves including the rectifying valve were coupled by inter-valve transformers of special design. The primary and secondary windings of each of these transformers consisted of a few turns of insulated wire on a laminated iron core of the shell type. The laminated iron sheets were very thin, so that the hysteresis and eddy current losses were small for currents of high frequency.

The audio-frequency valves including the rectifying valve were coupled by inter-valve transformers, the design of which is now generally well known. The listening telephone of 4,000 ohms supplied with this amplifier is usually inserted in the anode circuit of the last valve. The connection and disconnection of the receiver in this way is accompanied by a deafening click, which is very annoying during observations of feeble sounds. This was avoided by connecting the receiver to the terminals of the secondary of an equal ratio transformer —the primary forming part of the anode circuit of the last valve. This modification did not affect the amplification to any appreciable extent.

It was proposed to carry out this measurement in the space afforded by two rooms totalling about 30 ft. each way, and therefore special precautions had to be taken to extinguish all disturbing radiation and limit the received radiation to that which could be controlled by suitable apparatus.

The source of audio-frequency was a fork* alternator of novel design ; which had been previously used for the measurement of audio-frequency amplifiers. The vibrations of the tuning fork of this alternator were maintained by a valve, and the circuit is shown in Fig. 1.



The Brown electro-magnets *B* and *C* were mounted close to the prongs of the tuning fork *A*. The coil of *B* was included

* Maintenance of the vibrations of a tuning fork," by W. H. Eccles, D.Sc., and F. W. Jordan, B.Sc., " The Electrician," June 20, 1919.

in the plate circuit of the valve *P.G.F.* and the coil of *C* was connected in series with a dry cell to the grid *G*. The tuning fork can be set in vibration by closing the filament switch when the Brown electro-magnets have been properly adjusted. This arrangement provides a very steady source of sound and alternate current of known frequency for long periods, and the only attention required is the renewal of the charge of the filament battery.

The purest tone from the tuning fork is obtained by adjusting the distance between the magnets and the prongs of the tuning fork to about 1 or 1·5 mm. The filament current is then adjusted to give the maximum intensity of sound, and then the desired A.C. in the plate circuit can be obtained by adjusting the voltage of the plate battery. The latter can be reduced to 8 volts without stilling the vibrations of the fork. The primary coil of the step-up transformer *T* (Fig. 2) and the 100 ohm. rheostat *R* (Fig. 3) are also included in the plate circuit of the valve.

The radiation from the circuit in Fig. 1 was very slight, and could not be detected with the amplifier at a distance of 20 ft.

A feeble source of radio-frequency waves for this measurement was afforded by the use of a Brown syntoniser (Fig. 2). The wave length of the oscillations was given on a circular scale attached to the variable condenser. The open coil of the oscillating fly-wheel circuit behaves as a radiator; but owing to the feebleness of the oscillations and the special precautions taken in this measurement, the direct radiation from this circuit could not be detected with the amplifier. A more suitable non-radiative feeble oscillator has since been designed for work of this character.

The voltage applied to the plate in this oscillator is that of the filament battery, and it was found with the aid of a slide potentiometer that the oscillations could be extinguished by reducing this voltage to about 3·8 volts. Since it was desirable to reduce the intensity of the free oscillations of this circuit to a minimum, a small accumulator *e* of 2·1 volts was connected in series with the secondary of *T*, and in opposition to the 6 volts of the filament battery. The intensity of the radio-frequency oscillations under these conditions in this circuit will be a function of the voltage at the terminals of the secondary coil of the transformer *T*, and vanishes when the total plate voltage falls below 3·8 volts. Other methods

of superposing the audio on the radio-frequency oscillations were tried but not with the same success.

The maximum positive voltage applied by T to the plate circuit of Fig. 2 was determined by measuring how much e had to be increased to extinguish the fork note as received by the French amplifier. This was found to be of the order of 10 to 12 volts. Thus the voltage from T was sufficient to ensure that the radio oscillations were broken up into approximately semi-period trains of waves as shown in Fig. 4.

The audio radiation from an oscillator of this type ought to be inappreciable. This was verified by connecting a telephone to a coil which was closely coupled with that of the oscillator. An additional confirmation of this was made by connecting a loosely coupled coil l direct to the amplifier about 20 ft. away. The note of the fork was scarcely detectable until the coil l was tuned with a condenser to the radio-frequency oscillations, and then the sound was quite deafening.

The amplifier V (Fig. 3) was installed in a quiet room 18 ft. away from the circuit of Fig. 2. The receiving coil M was connected to the tuned circuit CN and to the input terminals L_1 L_2 of amplifier. The coil L was connected in series with l, which was coupled with the oscillating coil of Fig. 2. The input energy to the amplifier was controlled by adjusting the distance between L and M. The distance between the circuits of Figs. 1 and 2 was 4 ft., and the extreme distance between amplifier and circuit of Fig. 1 was 22 ft.

To be quite certain that no detectable radiation except the controlled portion reached the amplifier, (1) the axis of the oscillating coil of Fig. 2 was made vertical, while those of L and M and the radio coils of the amplifier were horizontal; (2) the leads from circuits of Figs. 1 and 2 to amplifier were encased in separate earthed lead sheaths; (3) the near point K of the oscillating coil of Fig. 2 was earthed; (4) other leads and circuits in the vicinity were removed, and when this could not be done were sheathed and earthed, and (5) the major part of the inductance N of the tuned receiving circuit CMN was a closed ring coil of a non-receptive character. Stray radiation could have been almost completely eliminated by enclosing the apparatus of Figs. 1 and 2 in earthed metal cases; but this would have given too much trouble. These precautions were effective in stopping stray radiation.

It was decided to select the fourth rectifying valve as a standard or unit with which to compare the amplifications of the various groups of other valves in this amplifier. The performance of such an unassisted valve does not differ very much from that of a crystal rectifier, and therefore its use as a practical standard is justified. The amount of energy transmitted to a valve or crystal rectifier depends to some extent on the electrical dimensions of the tuned receiving circuit. It was found that so long as the inductance and resistance of ringed coil *N* is kept within reasonable limits, the amplification is not much affected. Since a resonant receiving circuit is used in most methods of reception no account is taken in this measurement of the energy accumulated by resonance in such a circuit.

The procedure which was adopted in making a comparison of the different groups of valves was to vary the input energy

Fig. 4.

to the receiving circuit *CMN* (Fig. 3) by means of the sliding coil inductance *LM* until the intensity of the fork note was equal to a comparison standard. A test with different observers showed that the range of adjustment of the sliding coils *LM* was equivalent to about 4 per cent. of the mean A.C. voltage applied to the receiving circuit. Thus with different groups of valves the relative voltage amplifications would be equal to the ratio of the mutual inductances of the coils *L* and *M* in the two cases—the energy amplification being equal to the square of this ratio.

A comparison standard of sound of the frequency of the fork was given by inserting the dial potentiometer *R* (Fig. 3) in the plate circuit of the fork alternator. The potentiometer consisted of two non-inductive dial resistances, one of tens and the other of units. The leads from the circuit of Fig. 1 to *R* were encased in an earthed leadt ube and the terminal *f* (Fig. 3) common to the telephone *H* and the rheostat *R* was earthed. The leads *m* about 1m. long were also encased in an earthed lead tube. Under these conditions no sound was audible in the telephone when the leads from this were con-

nected through the small switch s to the same point f of the potentiometer R. The non-radiative character of this arrangement was tested by moving the contact g to the other end of R so that the full $P.D.$ was applied to the leads m and the charge over switch s was placed in position where it connects the telephone H to the output terminals of the equal ratio transformer T_2. Under these conditions no sound was audible in the telephone, but if one hand was brought close to the fourth valve and the other stretched out towards R the fork note became audible. Reception of the latter kind was, of course, intentional, and does not occur in practice. The advantage of this as a comparison standard of sound

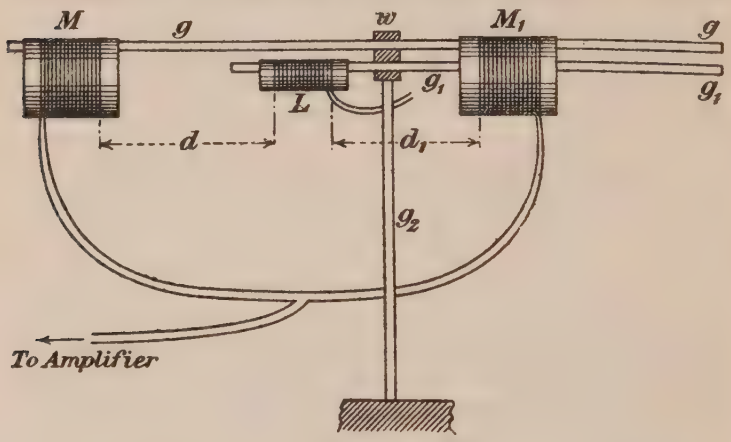


Fig. 5.

is that a change of the fork alternating current will affect both the radio frequency and oscillations and this standard equally.

The method used for calibrating the mutual inductance between L and M presented some novel features, and is particularly applicable to this case where L and M are used for controlling the input energy to an amplifier.

The mutual inductance consisted of two coaxial coils L and M sliding on glass rods gg (Fig. 5), and the distance between them could be increased up to 130 cm. The advantage of this particular type of inductance is that the capacity effect between the coils is inconsiderable until the distance between them becomes small. The coil L consisted of 227

turns of No. 30 covered wire on a cylindrical tube of length 16·6 cm. and diameter 6·2 cm. The secondary M consisted of 66 turns of No. 20 wire on a tube 7·3 cm. long and diameter 10·6 cm. A block of wood w was paraffined and drilled longitudinally to receive the glass rods gg and $g_1 g_1$. The lateral distance between g and g was such that the coils L and M were co-axial when slung from the rods. The ends of the glass rods were supported by paraffined wooden clamps, and the rods were prevented from sagging at the centre by the glass rod strut g_2. Clips to grip the glass rods lightly were fitted to the sliding coils L and M to maintain the axes of the coils and glass rods parallel to each other. The coils were in this way isolated from surrounding objects, and secondary radiation and indirect transmission from L to M were eliminated. The mounting of the coils in this way does not permit of the highest accuracy being realised in the measurement of the mutual inductance, but in this work an error of 1 or 2 per cent. in the estimation or reproducibility of this quantity is not of much importance.

The capacity effect between L and M was tested by interposing an earthed screen of fine parallel wires between these coils. Only a very small change in the intensity of the fork note was noticed when the earth connection was removed from the screen unless the coil M was near enough to enclose a portion of L. The insignificance of the capacity effect is probably due to the fact that the radio-frequency oscillations were generated at a low voltage, and that one point k of circuit of Fig. 2 was earthed.

The mutual inductance between two coaxial coils is a function of the dimensions of the separate coils, their distance apart and the product of the numbers of turns in the coils. If the number of turns in one coil be halved and the other dimensions be unaltered, the mutual inductance will be halved. This gives the clue to the construction of a binary scale of mutual inductance. Another coil M_1 was constructed of half the number of turns of M by winding an equal tube with twin lengths of the same wire and connecting the lengths in parallel. Thus the dimensions of M_1 and M were the same, whilst the number of turns on M_1 was half that on M. The two coils M and M_1 were arranged on opposite sides of L and connected in opposition to the tuned circuit CN of the amplifier. The self inductance of the closed ring coil N was $0{\cdot}7\times10^{-8}$ henries and was much greater than that of M.

Suppose that it is desired to construct a binary scale of mutual inductance starting with M, say, at a distance of 1m. from L. M is placed at the latter distance and the position of M_1 is adjusted until the note of the fork is suppressed in the telephone H. This position of silence is well marked provided that the intensity of the radio-frequency oscillations is sufficiently great or the distance between L and M not too considerable. Let d and d_1 be the respective distances of M and M_1 under these conditions. Then the mutual inductance of L and M at distances d_1 is twice that at the distance d. M was next moved to distance d_1 from L and the adjustment of M_1 repeated. In this way a complete binary scale of Mutual Inductance between L and M was obtained and graphed for the purpose of this measurement. A ternary scale could be obtained in a similar way by making the turns of M_1 a third of those of M. A scale of this description is particularly applicable to amplifier measurement and is to be preferred to calculation of the mutual inductance as this takes no account of capacity effects and secondary radiation or indirect transmission, and in addition is extremely laborious.

If the coil L be made in two equal sections and these be traversed by the oscillatory current in opposite directions, then the mutual inductance between L and M will fall off still more sharply with increasing distance from L—approximately as the inverse of the fourth power of the distance between L and M. A radiating coil of this kind would be useful where amplifications of a higher order had to be measured.

Close coupling of M with L and ultimately with the coil of the oscillating circuit in Fig. 2 must be avoided. The existence of this can be easily detected by the use of the tuning condenser C in the receiving circuit since the reactionary effect of currents in M on L is to alter the wave length and sharpness of tuning and for very close coupling to set up oscillations of two different wave lengths. For this reason M was not brought too near to L, the inductance of L was made small in comparison with that of l and the coupling of l with the oscillating coil was made loose.

A final test for stray radio-frequency radiation was made in the following way: L was removed and the ends of the leads where they projected from the lead sheath were joined together. The receiving circuit CMN of amplifier had pre-

viously been tuned to the radio-oscillations. No sound was audible in the telephone until the coil *M* was moved to a position where it enclosed the exposed leads to *L*.

The amplifier was quite noisy at times owing to the presence of electrical machinery in the building and neighbouring factories; but there were periods when it was very quiet and measurements could be conducted quite safely.

The next step was to dissect the amplifier so that any arrangement of valves could be examined. The top covering plate of ebonite was raised and supported in the vertical position and the wooden back was turned down on its hinges. Nearly all the leads inside were disconnected and labelled. The leads where necessary were lengthened and the whole amplifier reassembled. The performance of the reassembled amplifier was found to differ but slightly from an unaltered *L*. I. amplifier. Thus the rearrangement and slight lengthening of the leads had no deleterious effect on the amplification. The amplifier was supported on layers of felt to exclude mechanical vibrations and the observations were conducted in a quiet room.

The fourth rectifying valve, which has been selected as a unit, was isolated together with its associated transformers from the rest of the valves. The comparison sound was made feeble by connecting *H* (Fig. 3) through switch *s* to the first 2 ohm section of the potentiometer *R*. In the other position of the switch *s*, *H* could be connected through the transformer T_2 to the secondary of the inter-valve transformer of this valve. The primary coil of the radio inter-valve transformer was connected by the terminals of the tuning condenser *C* of the receiving circuit. The coil *M* was then moved to position where the fork note from the valve was equal to the comparison sound. The inter-valve transformers were associated with the valve in this measurement; but a slightly better result was obtained by the unassisted valve. The adjustment of *M* was made for wave lengths of 1,500 m. and 2,500 m. and also for different filament currents.

The fifth valve was then coupled with the fourth, and the adjustment repeated. The voltage amplification was then expressed as being equal to the ratio of the mutual inductances of the coils *L* and *M* in the two cases. The sixth valve was then coupled with the fourth and fifth. The amplification of the audio-frequency valves was found to be about eight to ten times that of the rectifying valve. The radio-frequency

valves were examined in the same way, and the amplification by these was of the order of 60 to 70 times that of the rectifying valve. The amplification of the assembled amplifier was about 500 to 700 times that of the rectifying valve at the same filament current and for a wave length of about 2,000 m. These figures must be squared to obtain the energy amplification. The actual amplification increases enormously as the filament current is increased, and the figures above only refer to a comparison of the groups of valves with the rectifying valve at the same filament current.

It was noticed that there was a change of character of the note with different groups of valves and the sharpness of tuning with condenser C varied from group to group. The latter is easily accounted for by the fact that N and M were connected in parallel with the primary coil of the inter-valve radio-transformers, whilst the former is accounted for by distortion of the wave form by the iron cored transformers. The tuning was very sharp in the case of the completed amplifier. The amplifier was usually much quieter with the switch on left depressed to stud R, although this is not the best position for the amplification of short waves. Retroaction and auto-oscillation of this amplifier can, if necessary, be regulated by the use of a solenoidal coil K (Fig. 3) connected in series with M and placed at a little distance from the radio-transformers of the first three valves. Retroaction can be regulated by moving K to or from the transformers. For a certain critical position of K the amplifier becomes self-oscillatory, and for a slightly less intense retroaction the amplification is much improved.

The object of this work was not to attain a high order of accuracy, but to devise some trustworthy method of comparing the performance of the separate valves of an amplifier and of different amplifiers. Such results are very useful in guiding one in the proper selection of valves, and the correct design of the electrical equipment of an amplifier.

Finsbury Technical College.

ABSTRACT.

The audio-frequency oscillations were generated by means of a tuning fork, which was maintained in vibration by a triode valve. The alternating-current voltage from the plate circuit of this valve was applied through a transformer to the plate circuit of a feeble radio-frequency oscillator. The radio-frequency oscillations were in this way separated into alternate semi-period trains of waves. The input

energy to amplifier was controlled by a sliding coil inductance. The radiating coil of this was loosely coupled through an auxiliary coil with the oscillating coil of the radio-frequency generator and the receiving coil was connected to the tuned receiving circuit of the amplifier. The receiving coil of this inductance was adjusted so that the intensity of the rectified oscillations, as received through the amplifier by the telephone, was the same as that of a standard source of sound of the fork frequency. The latter standard was furnished by applying a small alternating-current voltage from the fork alternator circuit to the receiving telephone. The voltage amplification under these conditions is the ratio of the mutual inductances of the sliding coils (1) without the amplifier and (2) with the amplifier. A method of calibrating the mutual inductance and also methods of eliminating strong radiation are detailed in the Paper.

DISCUSSION.

Mr. F. E. Smith congratulated Mr. Jordan on the results he had obtained. The difficulties of the method were undoubtedly considerable. At the National Physical Laboratory measurements of a similar nature had been made, and with similar apparatus except for the air core transformer, and the means for breaking up the train of undamped oscillations. There were, however, other objects in view than the measurement of amplification, and these had led to the introduction of a device for quickly changing the intensity of the oscillatory current. With regard to methods for producing a tonic train of undamped oscillations he had found some years ago that it was possible to do this by introducing two oscillatory circuits in a single anode circuit of a valve, one of these oscillatory circuits being of radio-frequency and the other of sonic frequency.

See also page 131 for comments by Mr. P. R. Coursey on this and the following Paper.

XIV. *On the Measurement of Amplification Given by Triode Amplifiers at Audible and at Radio Frequencies.* By F. E. Smith, *F.R.S.*, *and the late* H. C. Napier, *M.A.* (*From the National Physical Laboratory*).

Received January 7, 1920.

1. *Measurement of the Amplification Given by Audible Frequency Amplifiers.*

Triode valves are used for a variety of purposes, but more especially as amplifiers of radio-frequency oscillations, as rectifiers of these oscillations and as amplifiers of the resulting groups of rectified oscillations, these groups being of audible frequency. In ordinary telephony, triode valves are desired to be amplifiers only, as any rectification leads to distortion.

The quantitative measurement of the amplifying powers of valves is a matter of considerable interest. In the early days of the war, with a three-valve set, voltage amplifications of many thousands and even of a million times were often spoken of, but never met with in our experience.

A set of four valves with their associated transformers is shown in Fig. 1. In many such sets the first valve is a rectifier and partial high-frequency amplifier, the other three valves being audible frequency amplifiers. Iron core transformers are then used between the first and second, the second and third and between the third and fourth valves. In the figure, the telephone is intended to be in series with the anode of the fourth valve at D_1D_2; but sometimes a transformer is interposed, the primary of which is in the anode circuit and the secondary is in circuit with the telephone. For amplification of audible frequencies only, an additional iron-core transformer is used between the source and the grid of the first valve. This is shown in the figure.

Measurements showed, as might be anticipated, that in an amplifier of this kind the transformers play an important part, and it was at times advantageous to substitute other transformers for those supplied with the set.

In amplifying sets for either audible or radio frequencies, but not both, the transformers between valves are similar, and, since an experimental receiving circuit is usually very dissimilar to the connecting circuits between the valves, amplification by a separate valve was first obtained in our experi-

ments, and the intensity of the note produced in a telephone in the anode circuit of this valve was taken as the standard of reference. The valve so used and the transformer associated with it were similar to those in the set. In Fig. 1 this reference valve is *A*, and it is the amplification of the three valves *B*, *C* and *D* which is intended to be measured. The

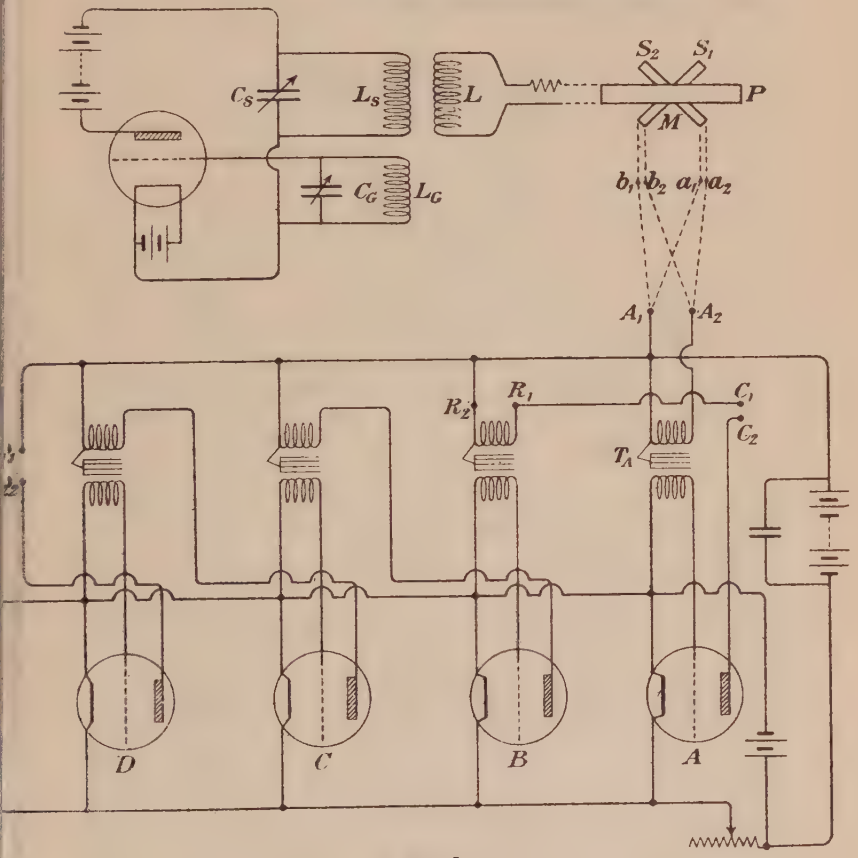


FIG. 1.

intensity of the standard note was usually adjusted at the source, so that signals could be just read with comfort.

In some early experiments a buzzer was employed as a source of sound, but the noise and general disturbance due to it were very troublesome, and it was displaced by a triode valve set generating oscillations of an audible frequency. The

anode oscillatory circuit consists of the inductance L_s and the condenser C_s, these being adjustable and of such values that oscillatory currents of almost any audible frequency can be obtained. The great advantages over the buzzer are the constancy of the frequency and intensity of the oscillations, and the fact that no audible note is produced until a telephone circuit is in some way coupled to L_s.

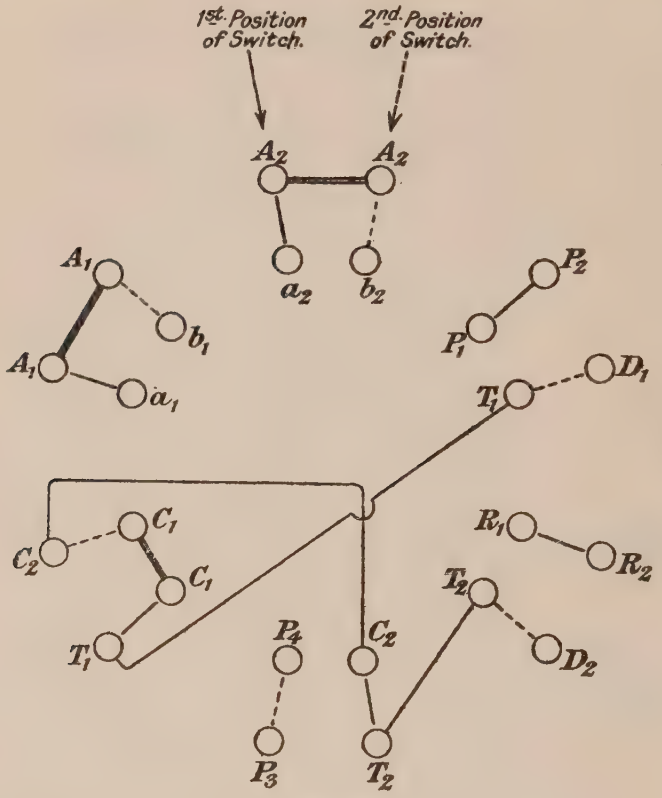


Fig. 1b.

A coil, L, is loosely coupled to L_s, and the induced currents pass through the primary P of an air core transformer, M. This transformer has two secondaries, S_1 and S_2, crossed at right angles and capable of rotating together about a vertical axis. The mutual inductance between the primary and either secondary was measured for various angular positions

of the latter by means of a Campbell inductometer. Either of the secondaries may be directly included in the grid circuit of the valve A or a transformer may be interposed. The anode circuit of A includes the primary of a suitable transformer, the secondary of which is in the grid circuit of the valve B. When the telephone (connected to T_1T_2, Fig. 1B) is included at C_1C_2 in the anode circuit of A, the primary of the transformer between the two valves is excluded from the circuit by a short-circuiting piece across R_1R_2. In these circumstances, suppose that the secondary S_1 of the transformer M is in circuit with the primary of the transformer TA; by means of a turning head (shown in Fig. 1B), S_1 is now disconnected, and the secondary S_2 is substituted, the telephone being simultaneously removed from the anode circuit of A and included at D_1D_2 in the anode circuit of the last valve; at the same time the short-circuit across R_1R_2 is removed. These changes are simultaneously made by a six-brush switch in a fraction of a second. The secondaries S_1 and S_2 are rotated with respect to the primary P until the intensities of the signals for the two positions of the switch are equal. The ratio of the mutual inductances between P and S_2 and P and S_1 is then a direct measure of the voltage amplification due to the valves B, C and D.

Amplifications up to 20 are conveniently measured in this way. If it is desired to measure greater amplifications, the number of turns on S_1 and S_2 may be different, or the switch may alter the number of turns in the primary P, the current through P remaining practically constant, or the value of the oscillatory current in L_sC_s may be altered. In the last case the ratio of the mutual inductances between P and S_2 and P and S_1 is the one in which fine adjustments can be made, and has to be multiplied by the ratio of the currents to give the amplification. In this way a series of three selected valves has been found to have an amplifying power as great as 300. Most of our measurements have, however, been made with one or two valve sets, the usual magnification obtained with one valve being from 8 to 12 and with two valves from 20 to 80. The big variation in the latter case is due to variation in the valves employed. If two single valves, each of which will, when the currents and voltages are nicely adjusted, amplify a note 10 times, be used in cascade, the amplification obtained is in general less than 100, for it is usually necessary to adjust the filament current to avoid hissing in the valves. This

trouble is, however, much smaller than it was a few years ago.

Fig. 1B shows the connections to a six-brush switch for making the changes referred to. The parts on Figs. 1 and 1B, which are indicated by similar letters, were connected together by leads. The telephone is connected to T_1 and T_2. A single brush connects two studs on a radius, and the angular move-

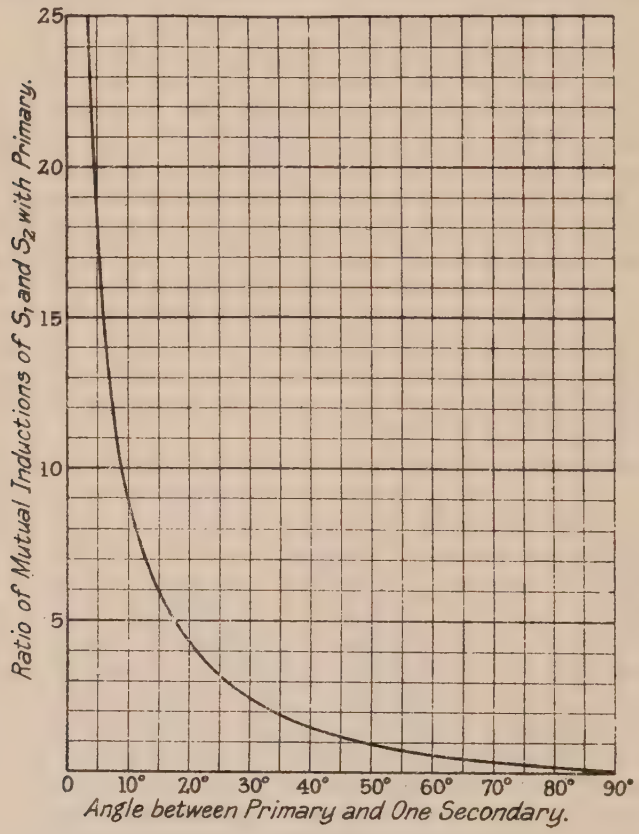


Fig. 2.

ment of the switch is limited to the small angle between two pairs of neighbouring studs. When more than 20 volts was applied to the anode circuits, the telephone was connected to the secondary of a suitable transformer, the primary of which could be placed in an anode circuit by connecting it to the studs T_1 and T_2 of the switch.

In making measurements the axes of the coils L_s, L_g and L were kept vertical and sufficiently far removed from the rest of the apparatus to prevent disturbing effects due to any direct action on the secondaries of the transformer M or any parts of the valve circuits. The axes of the coils of M were horizontal. Loops in leads were avoided, and when P was short-circuited there was a negligible amount of energy passing into the valve circuits from the telephonic frequency circuit.

Fig. 2 gives the ratios of the mutual inductances of the secondaries S_1 and S_2 with the primary P for angular displacements of the secondaries. For either coil the ratio is a maximum when the plane of the coil is in the plane of the primary.

It will be seen that if the amplification is greater than 20 the angle between one secondary and the primary will be less than 5 deg. The primary P was therefore divided into three parts, so that the number of turns in circuit with L could be varied, the ratio of turns used being 1 : 10 : 20. In a later apparatus the number of turns on a secondary can be varied.

Comparison with the Shunted Telephone Method.

Measurements were made to compare the results obtained by the method already described with those obtained by a shunted telephone method. The latter was a slight modification of the method usually employed, the energy of the current received in the telephone when two or more valves were used being cut down by a shunt until a balance was obtained against the energy of the current derived from one valve. The telephone was not shunted to secure silence. In this shunted telephone method the oscillatory energy in the grid circuit of the first valve was constant, whereas in the method previously described it was varied. If, under the conditions of the experiment, L_1=inductance of the telephone, R_1=resistance of the telephone, and R_2=resistance of shunt, then

$$\text{Current amplification} = \frac{\sqrt{(R_1+R_2)^2+L_1^2\omega^2}}{R_2}$$

In our experiments the resistances and inductances of the telephone and the shunt were measured at the frequencies employed in the amplification tests. In a particular case, when the frequency was 574 per second, the Sullivan telephone used had an inductance of 1·54 henries and a resistance of

3,900 ohms. The shunt resistance was of negligible self-inductance.

As examples, the following results are given :—

Valves.	First method.			Shunt method.	
	Angle of balance.	Ratio of turns in primary P, the current in P being practically constant.	Magnification	R_2 ohms	Magnification (approximately).
K_1	8°	1	12	660	11
K_2	$7\frac{1}{2}$°	1	$12\frac{1}{2}$	640	13
K_3	10°	1	$9\frac{1}{2}$	740	10
K_3	45°	10	10	700	10
K_1+K_3.....	20°	10	45	185	37
$K_1+K_2+K_3$	6°	10	160	48	140
F_1	12°	1	$7\frac{1}{2}$	920	8
F_2	10°	1	9	850	$8\frac{1}{2}$
F_3	10°	1	9	820	9
F_1+F_2	$17\frac{1}{2}$°	10	50	170	40
F_2+F+F_3..	7°	20	260	33	200

There was some hissing produced when the three valves were used in cascade which rendered it necessary to slightly reduce the filament current.

For the shunted telephone method the number of turns in the primary P was kept constant, and the angular reading of the secondaries was also kept constant at 45 deg. To facilitate the readings, the six-brush switch was modified as shown in Fig. 3. The variable resistance R_2 was inserted between the studs marked T_1 and P_3, and P_4 and T_2 were connected together. R_2 was adjusted until equality of sound was obtained for both positions of the key. The reading of R_2 was all that was necessary for the shunt method. For the other method, the switches K_1 and K_2 were opened, and the secondaries of the transformer M were turned until equality of sound resulted. This gave the reading for the first method. Thus the comparison of the two methods could be made in a minute or thereabouts.

The two methods are distinctly different. In the first method the amplification is measured by *reducing* the incoming power, while in the second method the incoming power remains *constant*, the amplification being measured by reducing the effect of the amplifying action. If the alternating potentials applied to the valves are within the limits of the grid voltages which correspond with practically straight line portions of the

anode characteristics, and if there is negligible grid current, the two methods are likely to agree, but not otherwise. This will be seen from a consideration of Fig. 4, which gives the change of anode and grid currents with change of grid voltage over a limited range. In the first method described in this Paper, if when one valve only is used the change of grid voltage on the valve is represented by AB, this will also be (for precisely similar valves) the change of grid voltage on the

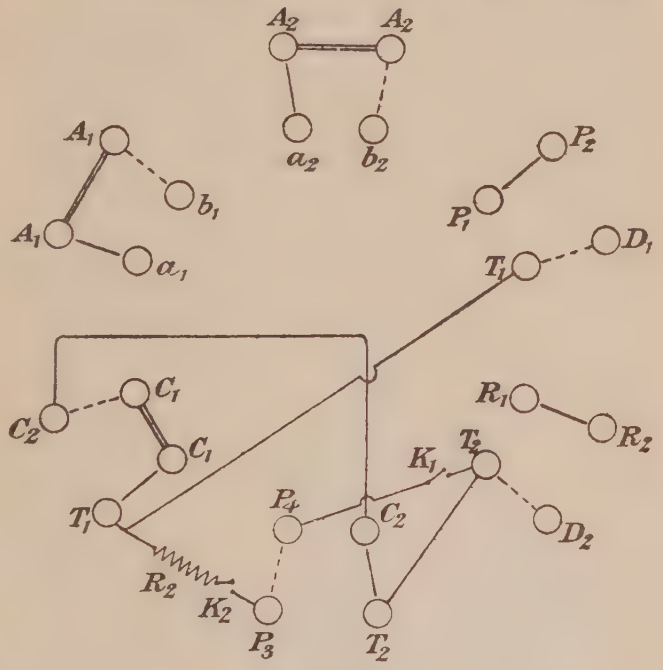


Fig 3.

last valve when a number are used, the change of oscillatory voltage on the first valve being red ced in order to achieve this result. In the shunted telephone method the oscillatory voltage on the first valve will still be AB, but that on the second valve will be much larger, and may extend over the bend of the characteristic, so that the ratio of the oscillatory grid voltage to the resultant change in anode current may change considerably from valve to valve. That this is so seems to be evident from the measurements, and since the purpose

of an amplifier is not as a rule to make a great noise in the receiving telephone, but to amplify either weak or inaudible signals, so as to read messages with comfort, the shunted telephone method does not in general give the results desired.

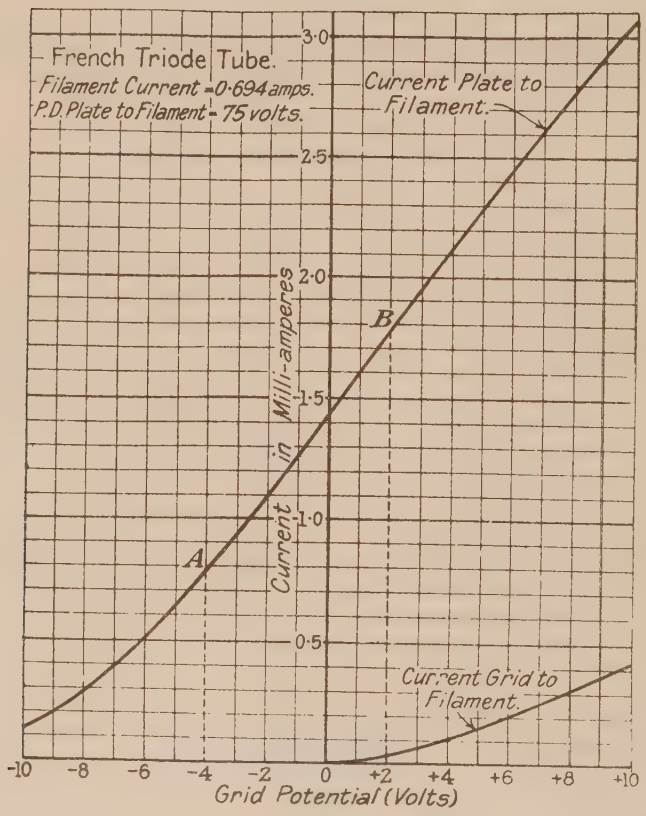


FIG. 4.

Fig. 5 gives the anode and grid characteristics of a Telefunken triode valve from a German submarine. It is rather soft, and good results were not obtained with such valves in cascade.

For valves to be satisfactory as telephone relays it is not only desirable for the rate of change of anode current with change of grid potential to be constant over the range worked over, but there should be negligible or constant grid current, or

otherwise some rectification and therefore distortion results. This will be referred to in more detail in the next section.

2. *Measurement of the Amplification of a Radio-Frequency Amplifier.*

Radio-frequency amplifiers differ from those intended for the magnification of audible frequencies. the most conspicuous

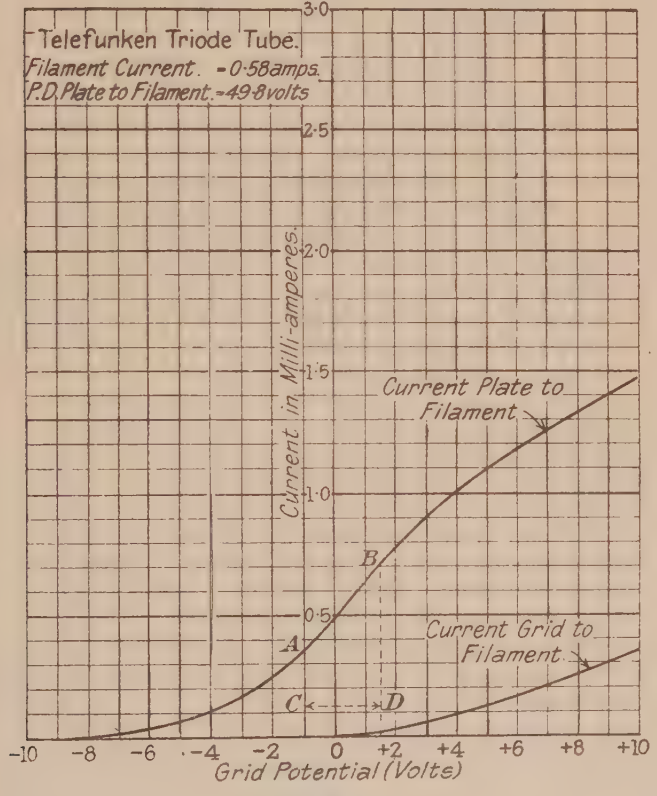


Fig. 5.

difference being in the inter-valve transformers, which are either without iron cores or have such in the form of very thin laminated sheets.

The method already described for measuring the amplification of an audible frequency set is not suited for one intended

to amplify radio frequencies. The capacity of parts of the circuits with earth results in very irregular distribution of current, and only when extraordinary precautions are taken can the coupling between the coils of any air core transformer be regarded as a true measure of the coupling between the circuits. Measurements have been made by a method closely analogous to that for audible frequencies and with fair success; but a simpler method was devised, and this is now described.

The source of radio-frequency oscillations was a single valve, V (Fig. 6), with a tuned oscillatory circuit, L_1C_1,

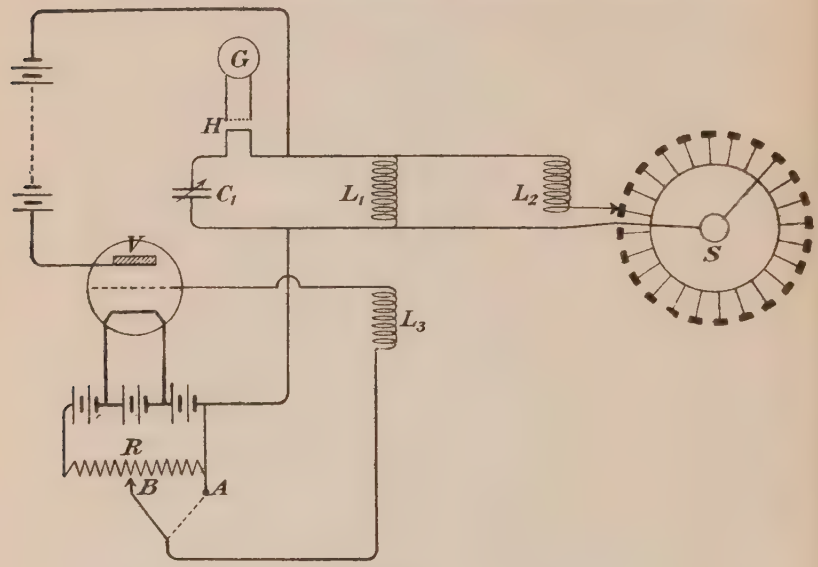


Fig. 6.

adjustable so as to give practically any frequency. In general, however, a frequency of one million per second was chosen for our experiments.

Since, after rectification, the amplification of a continuous train of waves of radio frequency produces no note of audible frequency in a receiving telephone, it is necessary either to break up the train into groups of audible frequency or to superpose some effect which will produce the desired result. It is easy to break up the train of waves at the source or at the receiving end, and it is equally easy at the source to superpose on the waves others of telephonic frequency, or at the receiving end to produce interference with a train of waves nearly equal

in frequency (heterodyne). For our purpose, it appeared best to break up the train of waves at the source.

The train of oscillations was broken up into groups by throwing the anode oscillatory circuit out of tune at regular intervals corresponding to the period of the audible frequency desired. A rotating shaft S (Fig. 6) carried a solid brass disc, from which 24 studs projected into a layer of vulcanised fibre, so that their surface was flush with that of the fibre. A brush made continuous contact with the brass disc, and a second brush made intermittent contact with the studs. On making contact between a brush and a stud the inductance L_2 was placed in parallel with the inductance L_1 of the anode oscillatory circuit, thus throwing the circuit out of tune and stopping the oscillations. This method was adopted in preference to breaking either the anode or grid circuits, as in the latter case the oscillations did not always commence again on make, and an irregular note was given in the telephone of the receiving circuit. Moreover, if the leads carrying a direct current be broken, a further wireless disturbance is set up, as experiment abundantly verified. The plan adopted, however, left nothing to be desired. In the experiments the frequency thus obtained was about 800 per second.

The essence of our method for measuring amplification lies in comparing the intensity of the note obtained from a single receiving valve, plus rectifier, with the intensity obtained from two or more valves plus the same rectifier. The intensities are made equal by adjustment of the incoming energy, but this is not done by a variation of a mutual inductance, as in the method for audible frequencies, but by a variation in the intensity of the radio-frequency current at the source.

The arrangement is shown in Fig. 6, where V is the generating valve and L_1C_1 the anode oscillatory circuit. L_1 was of very low resistance. The grid inductance is L_3, but there was no tuned grid oscillatory circuit. A heater, H, with separate thermo-junctions, was included in the anode oscillatory circuit, and the current accurately measured. Several heaters were made and carefully adjusted in resistance, so that any one could be substituted for any other one in the oscillatory circuit without any measurable effect on the current or on the tuning. The same galvanometer was used throughout the experiments, but several heaters were necessary, as the current was varied from a few milliamperes to an ampere or more. For the heating wires used, the high frequency resistance was less than

0·5 per cent. greater than the steady current resistance, so that calibration of a combined heater and junction was easy. Variation in the generated current was brought about by altering the grid potential. In general, the first grid potential in a measurement corresponded to that of the point A and the second to that of a point B, which was adjustable. The change from A to B was brought about by a switch, and the position B was varied until equal intensity of received notes was obtained when one valve and rectifier was used as receiver for the A position and several valves and the rectifier for the B position. After obtaining the balance, the oscillatory currents in the anode circuit were read off at leisure. Their ratio was the value desired.

Previous experiments had indicated a small change of wave-length when the grid voltage was varied over a considerable

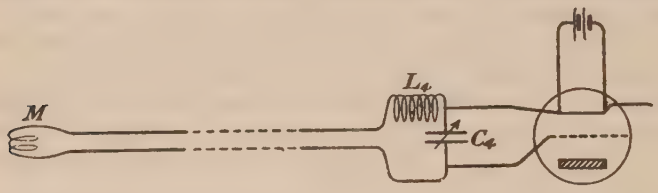


Fig. 7.

range, and it was necessary to determine to what extent this was a disturbing influence. To do this, a secondary oscillatory circuit was set up and adjusted so that the heterodyne beat frequency was about 780 per second. After an adjustment of the grid voltage of the first valve circuit to reduce the oscillatory current to 1 per cent. of its former value, the heterodyne beat frequency was about 200 per second; but the note which was formerly the higher was now the lower, so that the change in radio frequency of the oscillations in the first circuit was about 980, corresponding to 0·1 per cent. However, in our experiments, the impedance in the receiving circuit L_4C_4 (Fig. 7) was appreciable, and both measurement and calculation showed the resonance curve to be such that the change in wave-length due to change of grid voltage of the transmitting circuit could have but a negligible effect on our measurements of amplifying power.

Direct radiation from the valve circuit to the amplifier set was in general appreciable, even when the distance between the sets was as great as 40 ft. Metal screens and compen-

sating coils greatly reduced the action, and a few measurements were made on the assumption that direct radiation was negligible. However, in the method finally adopted, direct radiation was *not* excluded. The radio receiving circuit consisted of the coil M, the inductance L_4 and the condenser C_4 (Fig. 7). When this circuit was tuned and the oscillatory current in L_1C_1 was 1 ampere the noise in a receiving telephone, after amplification and rectification by three or four valves, could in general be heard very many yards away. It could be reduced by adjustment of the directions of the axes of L_1, L_3, M and L_4, and this was usually done. When the receiving circuit was thrown greatly out of tune the note was scarcely detectable, indicating that the receiving action of the valve leads, &c., was negligible. The axes of the coils L_1 and L_3 were made vertical, and that of L_4 horizontal. The coil M could be turned in any position.

The anode and grid characteristics of all the valves were found previous to any amplification measurements being made, and the grid potentials of the radio amplifying valves were adjusted for favourable amplification but poor rectification. The last valve in a set was of the same type as the others, but the grid potential of it was adjusted for favourable rectification.

Any method for measuring the amplification only of radio frequencies is, however, necessarily difficult, because in practically all cases when the filament currents and anode and grid potentials are adjusted for most favourable amplification there is also some rectification. Referring to Fig. 5, the part AB of the anode characteristic may be taken as a straight line, and the rate of change of the anode current with change of grid potential may be regarded as constant. If, therefore, the range of the oscillatory voltage lies within CD, and if these oscillatory voltages be symmetrical about the mid-point, there will be no rectification; but at C the grid current is zero, while at D it is 20 micro-amperes, and it rises with increasing rapidity as the grid potential is increased. If, therefore, the plate of the condenser C_4, which is connected to the grid, is charged positively by an amount corresponding to D, there will be a grid current, and therefore a leak; but when it is charged negatively by an amount corresponding to C there will be no grid current and no leak. Thus, it happens that in general the positive half of the incoming wave is cut down by a leak from the grid to a greater extent than the negative half. In

other words, the potential variations impressed on the condenser and grid are not only cut down but are slightly rectified by the above action. In radio work, however, this is of little importance, and our measurements were made under practical conditions.

For comparison purposes, the standard note was that obtained from one amplifying valve and one rectifying valve, the telephone being included in the anode circuit of the latter or coupled to it by means of a suitable transformer. One or more radio-frequency valves and transformers were then added, and the resultant note reduced in intensity to that of the standard by reducing the current in the main oscillatory circuit. The ratio of the currents was taken as the amplification. The change from one condition to the other was made in a fraction of a second by means of a multiple brush switch, as in the method already described for audible frequencies. No change of tuning was made, and no interference of the main circuits was permissible, except for the adjustment of the grid potential of the valve V. The shunt resistance R was non-inductive. The values obtained with the radio-frequency valves were comparable with those for audible frequency. A few checks on the method were made, of which the following is an example : With two radio amplifiers and a current of 20 milliamperes in the circuit containing L_1C_1 a note of very moderate intensity was obtained. The current was increased five times to 100 milliamperes, and the note restored to its original intensity by shunting the telephone, of which the inductance and effective resistance were known at the audible frequency experimented with. The shunt value was such as to give a ratio of currents 4·8. This check was considered very satisfactory.

The writer desires to express his thanks to Mr. Albert Campbell and to Mr. D. W. Dye for many suggestions in connection with the measurements.

ABSTRACT.

The measurement of amplification at audible frequencies which is described is a mutual inductance method, the alternating voltage applied between the filament and grid of the first valve being varied by quickly changing the connections to an air-core transformer having two secondaries at right angles, which secondaries are capable of rotation so as to give any desired ratio of the mutual inductances between the primary and the respective secondaries. The source of alter-

nating voltage is a triode circuit having such capacity and inductance in the oscillatory portion as to give currents of a sonic frequency. The standard intensity of note is such as to enable signals to be read with comfort, and is obtained by adjustment of the source of alternating current. The first note is obtained when the telephone is in the anode circuit of an auxiliary valve, and the second when the telephone is transferred to the anode circuit of the last valve of the amplifying set, changes also being made in the applied alternating voltage, and in the connections between the valve circuits. All of these changes are brought about by a six-brush switch in a fraction of a second, so that readings are quickly obtained.

The method is compared with a modification of the shunted telephone method, and very good agreement is obtained when the amplifying values are comparatively low. For values of a high order such as 200, it is shown that the two methods are not likely to give the same results, the method described in the Paper being the better one.

In the measurement of amplification of a radio-frequency amplifier an undamped train of oscillations is broken up into groups of sonic frequency by shunting intermittently the condenser in the oscillatory circuit by an inductance of low resistance. A sonic train of oscillations is thus produced.

The receiving circuit is very similar to that used for audible frequency amplification, but the measurement of the amplifying power is made by quickly varying the current at the source, and not by a change of mutual inductance. between the two circuits.

DISCUSSION.

Prof. FORTESCUE said it was an advance to have a method involving the comparison of two sounds. Curiously enough, he had used this principle before the war with crystal detectors, and had given it up because of the difficulty of getting the two notes of similar character.

Mr. P. R. COURSEY (communicated): These two Papers by Messrs. Smith and Jordan bring forward some interesting points in connection with the measurement of the amplification factor of valves, and also raise the question as to the best method of carrying out such measurements. The arrangement used by Mr. Smith for the low-frequency measurement is particularly interesting, and should provide a very accurate method of carrying out such tests. The agreement obtained between the readings obtained and those given by the shunted telephone method also appears suprisingly good, although it is very doubtful whether the same accuracy is obtainable by the shunted telephone method as ordinarily employed in a wireless receiving station. The observed magnifications as given by the shunted telephone method are apparently less than those given by the first comparison method in the Paper for the larger amplifications. This is, of course, to be expected from the fact that when making measurements by the shunt method the amplitude of the oscillations is larger than in the first case, and therefore one would expect that the amplification would fall off owing to the bends of the characteristic curves. The shunted telephone may be looked upon rather as giving an indication of the " response " of any given detector or amplifier rather than a measure of its ultimate " sensitiveness."

As far as measurements of radio-frequency amplification are concerned, the method that is probably the most commonly used is that in which a steady source of oscillations is used at the transmitter and the coupling between the transmitter and receiver coils is varied in a known manner. With this method, as has been pointed out by Mr. Jordan, difficulties are experienced owing to the capacity between the two coils; but in general

such difficulties can be overcome by a suitable earth screen, and, if necessary, by earthing the adjacent points of both transmitting and receiving coils. The screening of high-frequency C.W. oscillations is, however, by no means easy, as anyone who has worked with multi-valve amplifiers will readily appreciate.

Mr. Jordan's modification of the usual variable coupling method by providing a comparison for the sound intensity in the telephones in each case should lead to considerably greater accuracy as compared with the more usual arrangement; but it would seem possible that a somewhat simpler arrangement could be obtained by using two independent receiving search coils coupled to the transmitting coil (preferably on opposite sides of it), and arranging the induced oscillations in one of these to be detected by a single valve, while those from the other coil are passed through the amplifier. Both the receiving valve and the amplifier could be connected to the same telephones with a throw-over switch, and a rapid and accurate comparison could then be made between the intensities of the resulting sounds in the telephone in each case, thus giving the direct measure of the amplification obtained by adjusting the couplings to the two search coils until equality of signal strengths is obtained.

An Instrument for Indicating the Hardening Temperature of Steel. *By the Hon.* C. W. Stopford *and* C. R. Darling.

(Exhibited at the Meeting on January 23, 1920.)

The instrument depends upon the fact that the best results are secured by quenching steel at a temperature just above that at which it demagnetises, and is used in conjunction with an electric resistance furnace with inductive winding. A pivoted soft-iron rod is surrounded by a coil joined in series with the furnace winding. The deflection of the iron rod in either direction moves an upright spring, and breaks the circuit of a bell or buzzer. In using, the instrument is placed near the furnace, and when the current is switched on the pointer deflects and breaks the bell circuit. By a screw movement the springs are restored to such a position that the bell just rings. On placing the steel articles in the furnace the increased flux causes the bell circuit to be broken; but on demagnetising, the pivoted iron rod comes back to its original position, causing the bell to ring. The indicator may be used with either direct or alternating current, and responds when only a small charge of steel is placed in the furnace.

A Thermo-electric Cell of Constant Voltage. *By* C. R. Darling.

(Exhibited at the Meeting on January 23, 1920.)

This cell depends upon the constancy of the E.M.F. developed by molten bismuth and aluminium over a wide range of temperature (Darling and Grace, "Proceedings," Vol. XXIX. Part I.). An iron vessel is provided with a side branch of silica tubing, about 10 in. long, both being filled with bismuth. An aluminium wire covered with graphite passes through the lid of the vessel into the molten bismuth, and forms the hot junction, the cold junction being similarly formed at the remote end of the silica tube, and kept in oil in a vacuum flask. On placing a burner beneath the vessel the E.M.F. rises to 15 micro-volts at the melting point of bismuth (267°C.), the cold junction being at 15°, at which voltage the cell remains constant over a further 300° It has been found useful as a closely approximate standard in measuring thermal E.M.F.s, and as a "set-up" against another E.M.F. when using a pyrometer indicator for measuring special ranges. The internal resistance of the instrument exhibited is approximately 0·5 ohm.

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CONTENTS.

PAGE

Discussion on Lubrication 1s

VII. First Steps in the Experimental Analysis of a Galvanic Cell. By Prof. W. M. Coleman 57

VIII. Radiation from a Perfectly Diffusing Circular Disc. (Part I.) By John W. T. Walsh, M.A. (Oxon), M.Sc. (Lond.). (From the National Physical Laboratory)..... 59

IX. A Comparative Method of Testing Thermionic Valves for Passing No Reverse Current at High Voltages. By N. W. McLachlan, D.Sc. (Eng.), M.I.E.E. (From the National Physical Laboratory) 72

X. On Recording and Reproducing Sounds by Means of Light. By A. O. Rankine, D.Sc., Professor of Physics in the Imperial College of Science and Technology..... 78

XI. On some Experiments in which Two Neighbouring Maintained Oscillatory Circuits Affect a Resonating Circuit. By J. H. Vincent, M.A., D.Sc..... 84

XII. Measurement of the Chief Parameters of Triode Valves. By W. H. Eccles..... 92

XIII. A Method of Measuring the Amplification of a Radio-frequency Amplifier. By F. W. Jordan, B.Sc..... 105

XIV. On the Measurement of Amplification Given by Triode Amplifiers at Audible and at Radio Frequencies. By F. E. Smith, F.R.S., and the late Mr. H. C. Napier, M.A. (From the National Physical Laboratory)..... 116

An Instrument for Indicating the Hardening Temperature of Steel. By the Hon. C. W. Stopford and C. R. Darling.... 133

A Thermo-electric Cell of Constant Voltage. By C. R. Darling 134